FY06-08

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DRAFT

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Section 1.0 INTRODUCTION

1.1 The Bates Linear Accelerator Center

Universities are the gateways for young people to enter science. Students are attracted to universities to receive an education and to work with the faculty research groups on the frontiers of science. To attract and retain the best young people it is essential that the students are stimulated by an active and exciting research environment at the university.

For over thirty years, the Bates Linear Accelerator Center has provided a university based laboratory where young people have been educated and trained in the research frontiers of electromagnetic nuclear physics. Bates has been a national user facility administered through the Laboratory for Nuclear Science (LNS) at the Massachusetts Institute of Technology (MIT) and has been funded by the Nuclear Physics Program Office at the United States Department of Energy (DOE). Over the decades at Bates, important measurements to probe the structure and properties of atomic nuclei have been carried out. Further, new experimental techniques in widespread use have been pioneered In addition, over 100 young physicists have written Ph.D. theses from more than 40 universities around the world on research carried out at Bates.

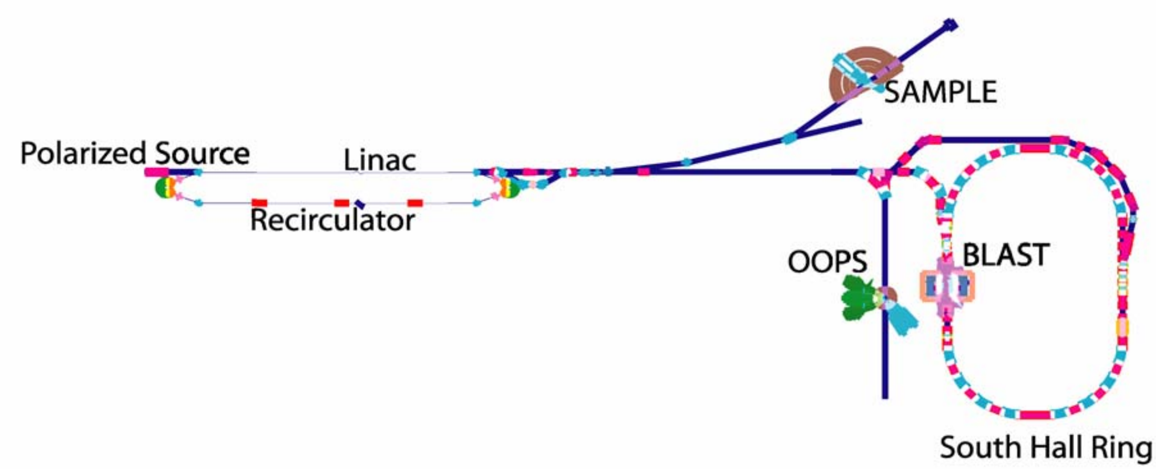


Figure 1.1. *Schematic layout of the Bates facility.*

At present, a new program of measurements using the Bates Large Acceptance Spectrometer Toroid (BLAST) is starting to take data. In 1999, it was agreed between MIT and DOE that upon successful completion of the BLAST program the national user facility would be phased out at Bates. At this time, it is understood that the last running with BLAST will take place in FY05.

MIT regards the Bates Linear Accelerator Center as a precious resource with tremendous potential for educating young scientists and for carrying out larger scale frontier research in an academic environment. Thus, with the knowledge that the Nuclear Physics user facility will be phased out in FY05, MIT-LNS has developed a vision for Bates as a Center for Accelerator Science with a significant research and engineering capability in support of the activities of the LNS faculty. Detailed consideration of the Center for Accelerator Science is underway by a committee of senior MIT faculty which is scheduled to report in Spring 2004.

In this document, the proposed research and engineering activities at Bates in the years FY06-08 are described. It is proposed that a staff of about 35 FTEs, with great expertise in essential areas of technical capability, play a major role in supporting MIT-LNS research at the Nuclear Physics flagship facilities at Jefferson Laboratory and Brookhaven National Laboratory. At Jefferson Laboratory, Bates staff would play a major role in the realization and execution of the important Standard Model test, Q_{weak}. At Brookhaven National Laboratory, Bates staff would play an essential role in realizing detector upgrades for STAR as well as playing a leadership role in the design of the electron-ion collider eRHIC. In addition, it is proposed to establish a micro-pattern detector facility at Bates. These tracking detectors have been identified as a high priority for the future. Further, a number of other research opportunities have been identified and will be considered over the coming years.

1.2 Research and Engineering Laboratory

It is proposed in FY06 to FY08 to retain a fraction of the present Bates staff to carry out research and engineering in support of the activities of the LNS faculty. The proposed research and engineering is primarily in support of major activities at the two flagship Nuclear Physics user facilities in the United States: Thomas Jefferson National Accelerator Facility in Newport News, Virginia and Brookhaven National Laboratory in Upton, New York.

There are two principal motivations for maintaining a research and engineering laboratory at Bates. Firstly, decades of support of Bates as a nuclear physics user facility has resulted in a highly trained team with considerable expertise in research and engineering in experimental physics. Retaining the essential and most valuable elements of this enterprise and harnessing it to the national program capitalizes on the decades of substantial investment. Secondly, Bates has been a very effective laboratory in which to educate and train young physicists over the decades. Its attachment to MIT, its proximity to the Boston area with its numerous universities and colleges and to the greater New England region make Bates a very attractive location for young people to work on technical projects.

1.2.1 Expertise at Bates

Over the decades, the relatively small staff at Bates has acquired substantial expertise in many of the important technical areas relevant to research in subatomic physics. These include:

- *Accelerator physics, particularly electron storage rings*
  The 1 GeV South Hall Ring with stored current up to 0.25 A, polarization in excess of 65%, fast spin-flip capability and long lifetime is a unique instrument.
- *RF technology*
  New solid-state high power switches were developed at Bates in collaboration with industry and are in regular commercial use.
- *Polarized particle injectors*
  The Bates polarized injector routinely delivers 70% polarized beam and a test bench has been developed to study all aspects of the source technology.
- *Specialized (inc. polarized and cryogenic) targets*
  Bates staff have successfully designed and constructed X Curie tritium targets, high power liquid hydrogen targets, and the Atomic Beam Source embedded in the BLAST toroid.
- *Detector development, design and construction*
  The SAMPLE, OOPS and BLAST detectors are all unique instruments used successfully at Bates.
- *Magnet and power supply technology*

Bates has a small but very skilled group who have successfully designed and constructed many unique magnetic systems from fast kickers in the ring to the large 6,700 A BLAST toroid.

- *Vacuum, particularly UHV technology*

  The vacuum group at Bates routinely meets challenges across different technical areas, e.g. the 10^{-12} torr vacuum in the polarized source and the 60 sccm high gas load of the atomic beam source.
- *Data acquisition and control*

  The EPICS control system is now standard at Bates and allows full automation of the ring filling and BLAST data taking.

While these fields of expertise are required for the currently proposed R&D projects, their strength will need to vary in time to match the varying requirements. It is proposed to retain expertise in each of the above areas. Note of the 35 FTEs proposed here, three would be newly hired staff physicists: two in the area of accelerator physics and one with expertise in micro-pattern detector development.

1.2.2 Educational Opportunities

Over 100 Ph.D. theses have been written on research carried out at Bates. A strong cohort of thirteen graduate students has been essential in the realization of BLAST and these students will graduate over the next several years. Further, there has consistently been a strong undergraduate presence at Bates over the years. In the SAMPLE experiment, undergraduate students from Caltech and the Univ. of Illinois played an important role in the data taking phase of the experiment. There is a daily shuttle from MIT campus to Bates and this allows easy access to the laboratory from the urban Boston area.

It is anticipated that as detectors and other pieces of instrumentation are prototyped and developed at Bates students will play a major role in this work. MIT undergraduates are actively encouraged to participate in the Undergraduate Research Opportunities Program (UROP) and thus can be attracted to work on research projects in Nuclear Physics at Bates. Many Physics Majors write Senior Theses on research topics and technical projects at Bates have been and will continue to be very suitable sources for such Theses.

1.2.3 Overview of Proposed Research

There are four main thrusts to the proposed research and engineering activities at Bates in the years FY06-08:

- **Q_{weak} at Jefferson Laboratory**

It is proposed that Bates physicists, engineers and technicians play a major role in the design, construction and commissioning of the Q_{weak} experiment at Jefferson Laboratory to test the Standard Model under the leadership of Prof. Stanley Kowalski. This capitalizes on Bates experience in constructing the BLAST spectrometer, in parity violation electron scattering, in polarized electron sources, Compton polarimetry and data acquisition.

- **STAR/RHIC-spin at BNL**

The Medium-Energy Group in the Laboratory for Nuclear Science at MIT is starting a new involvement at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) under the leadership of Professor Bernd Surrow within the STAR collaboration, which focuses on the collision of polarized protons to gain a deeper understanding of the spin structure and dynamics of the proton in a new, previously unexplored territory.

It is proposed that MIT-Bates plays a major role in the STAR tracking upgrade as well as participate in the STAR DAQ upgrade and the forward calorimeter upgrade [1.2.1]. Those upgrade efforts are key elements of the future RHIC SPIN program.

This capitalizes on MIT-BATES expertise in detector design, mechanical engineering and data acquisition.

- **Formation of a micro-pattern detector facility at Bates**

Several groups within the Laboratory for Nuclear Science at MIT are strongly pursuing GEM-type tracking detectors at future experiments such as for the STAR tracking upgrade, the eRHIC tracking system and detector systems at other future collider facilities. Those efforts will require a clean room laboratory to handle, inspect and test GEM-foils besides the actual detector assembly. Such a dedicated micro-pattern detector facility is not available as of now within the US nuclear and particle physics community.

The MIT Bates laboratory is an ideal location to pursue such a facility with its tremendous resources of highly skilled staff and infra-structure to carry out a complete GEM-type tracking detector construction effort from the test and assembly of individual GEM detector modules to the final integration into a larger detector structure.

A micro-pattern facility at MIT-BATES has enormous educational benefits. It will provide an ideal learning environment for undergraduate and graduate students and a stimulating research facility for future research associates at the forefront of future detector R&D and construction efforts in an academic environment. It will provide the means to attract and retain the best young people for an active and exciting research program.

This is a unique opportunity for MIT-BATES laboratory within the US nuclear and particle physics community since such efforts have so far been concentrated outside the US.

These considerations led to the proposal to establish a micro-pattern detector facility at MIT-Bates together with the appointment of a research physicist with demonstrated strong leadership skills in micro-pattern detector development to focus on the advancement of this promising tracking technology.

- **eRHIC accelerator design**

Bates physicists have played a leadership role in the identification of a high luminosity electron-ion collider as the next generation accelerator for the study of the fundamental structure of matter. Prof. Richard Milner has been a leader in the development and presentation of the scientific case to the international hadronic physics community. Dr. Christoph Tschalaer has been a leader in the development of the design of the electron-ion collider over the last several years. At present a team of accelerator physicists at Bates is working on the preliminary design of the eRHIC design in collaboration with physicists at Brookhaven National Labortaory, DESY, and the Budker Institute in Novosibirsk, Russia. Dr. Manouch Farkhondeh is coordinating the production of the Zero-Order Design Report (ZDR) for eRHIC, scheduled for Spring 2004. In the years FY06-08 it is proposed to continue the design of the eRHIC electron-ion collider. It is expected that the electron-ion collider accelerator physics research would constitute a significant activity at the future Center for Accelerator Science and Technology.

In addition, LNS faculty have identified a number of promising other research opportunities. These will be considered and may develop into significant research projects at a future date These are described in detail in section 2.5.

1.3 Center for Accelerator Science and Technology

There is strong interest across MIT in creating a Center for Accelerator Science and Technology. It is realized that accelerators are essential for frontier exploration in many

fields of science. Further, educating and training young accelerator scientists has been identified as a national priority. With LNS taking the lead role, MIT scientists in the Departments of Physics, Nuclear Engineering and Electrical Engineering over the last six months have been exploring the concept of a Center for Accelerator Science and technology focused on the Bates site.
In December 2003, Dean of Science Silbey charged a committee of MIT faculty to seriously consider the creation of a Center for Accelerator Science and Technology and to understand what is required for it to be successful. The committee is chaired by Professor of Physics Stanley Kowalski, has membership from across several Departments and Schools at MIT and is scheduled to deliver a report within several months.

An essential reason for creating such a center at MIT would be the education and training of young accelerator scientists. A curriculum in accelerator science would be developed and overseen by a committee of faculty drawn from different MIT departments. A student in a given department, e.g. physics, would carry out research under a physics faculty advisor in this Center and would be granted a degree in Accelerator Science. The educational component could be initiated in a straightforward fashion assuming that funding for student support is available.

A Center for Accelerator Science at MIT would naturally utilize the existing accelerator complex at Bates. This would be used both for educating students and as an essential component in frontier research. The charged particle sources, the linear accelerator and the South Hall Ring would be essential to the activities of this Center. In addition, the electron beams at Bates could be used for testing and calibration of detectors. Thus, MIT is in discussion with DOE concerning the accelerator complex in the post-user facility era of Bates.

Section 2.0 PROPOSED RESEARCH

2.1 Q-Weak: Measurement of the Proton's Weak Charge

S. Kowalski

2.1.1 Introduction

A major new initiative is under active development at Jefferson Laboratory. The goal of the Q_{weak} experiment is to measure the proton's weak charge $Q_W^p = 1 - \sin^2\theta_W$ to the highest precision. The Standard Model makes a firm prediction of Q_W^p, based on the running of the weak mixing angle $\sin^2\theta_W$ from the Z^0 pole down to low energies, corresponding to a 10 σ effect in our experiment. A significant deviation of $\sin^2\theta_W$ from the Standard Model prediction at low Q^2 would be a signal of new physics. Agreement would place new and significant constraints on possible Standard Model extensions.

The proposal received the highest possible scientific rating from the Jefferson Laboratory Program Advisory Committee (PAC) in January 2002. Following a successful Technical Review at JLab in January 2003, a funding package to support the equipment construction totaling approximately \$3.4M US has been put in place, provided by Jefferson Laboratory, US DOE, NSF and NSERC in Canada. The experiment is moving forward on an aggressive construction schedule. The objective is to install equipment in Jefferson Laboratory Hall - C by 2007.

2.1.2 Physics Motivation

Precision tests have played a crucial role in elucidating the nature of the electroweak interaction. Current experiments place constraints on the Standard Model and on proposed scenarios for extending it. Measurements at the Z^0 pole have constrained the weak mixing angle $\sin^2\theta_W$ to impressive precision at that energy scale. The Standard Model predicts a shift of $\Delta\sin^2\theta_W = +0.007$ at low Q^2 with respect to the Z^0pole best fit value of 0.23113 ± 0.00015. This shift would represent a 10% effect in the running of the weak mixing angle in our experiment, including both experimental and theoretical errors. A precision study of the evolution of the weak mixing angle to lower energies has not yet been successfully carried out. Testing this prediction requires precision measurements at different energy scales with well understood uncertainties so that one can interpret the results with confidence.

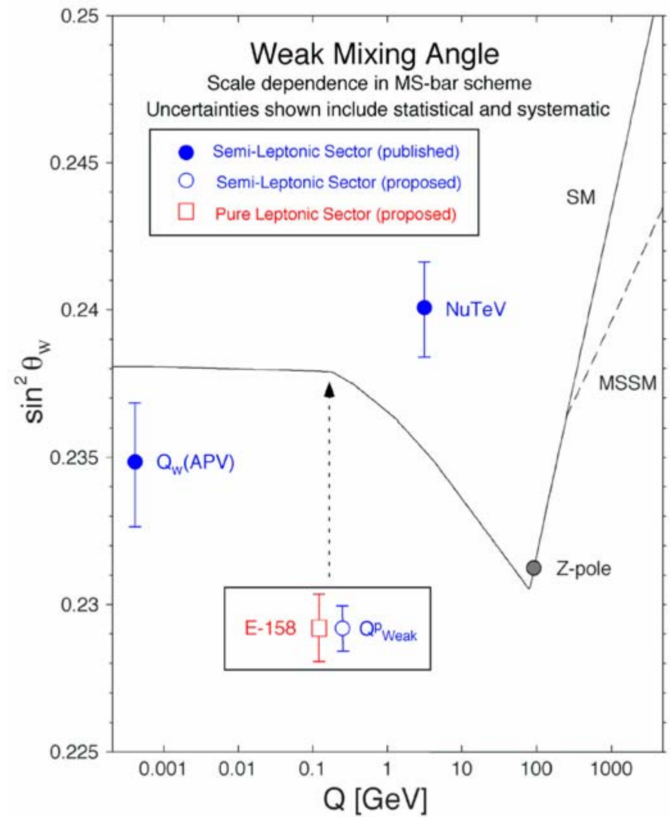


Figure 2.1.1. *Calculated running of the weak mixing angle in the Standard Model. Data points are from the atomic parity violation experiment on Cs, the NuTeV experiment, and from experiments at the Z^0 pole. Also shown are anticipated error bars for Q_{weak} and the Moeller experiment at SLAC.*

Figure 2.1.1 shows the Standard Model prediction for $\sin^2\theta_W$ together with existing and proposed world data. The very precise measurements near the Z^0 pole set the scale of the curve. Its shape must be tested at different energies. At present two experiments test the evolution of $\sin^2\theta_W$ at lower energies at a precise level – one in atomic parity violation (APV), and another from high energy neutrino-nucleus scattering (NuTeV) which shows a 3σ deviation above expectations. Both of these results suffer from complications in theoretical interpretation which limit their physics impact. A recently completed experiment at SLAC, E158, tests the running of the coupling constant in the purely leptonic sector, electron-electron scattering. It is not expected to reach a precision comparable to Q-Weak. The Q-Weak measurement at JLab will be preformed with much smaller statistical and systematic errors than all the other low energy experiments. It should have a cleaner theoretical interpretation.

2.1.3 Experiment

The Q-Weak collaboration will carry out a high precision measurement of the proton's weak charge, $Q_W^P = 1 - 4\sin^2\theta_W$ by measuring the parity violating asymmetry in elastic electron-proton scattering at very low momentum transfer:

$$A = (\sigma_+ \sigma_-)/(\sigma + \sigma-) = Q^2 Q_W^P + Q^4 B(Q^2)$$

where σ_+ and σ_- are cross sections for positive and negative helicity incident electrons and $B(Q^2)$ is a hadronic contribution to the asymmetry. Other parity violating electron-proton scattering experiments will be used to constrain hadronic corrections to the data. The experiment would be carried out using a 1.16 GeV electron beam at a scattering angle of 9° and a momentum transfer of $Q^2 = 0.03\ (\mathrm{GeV/c})^2$. The 180μA, 80% polarized beam will be incident on a 35cm liquid hydrogen target. A 2200 hour measurement of the parity violating asymmetry will determine the proton's weak charge with 4% statistical and systematic errors. The weak mixing angle $\sin^2\theta_W$ would be determined to ±0.3%. This accuracy is comparable to other high energy single channel measurements.

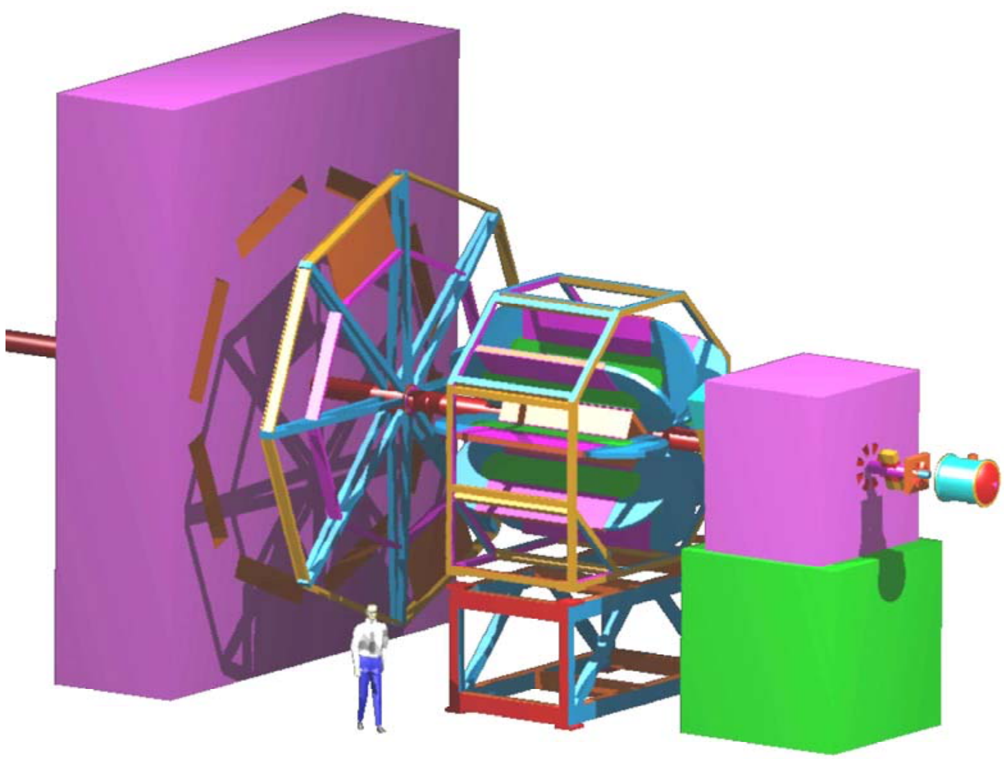


Figure 2.1.2. *Layout of the Q_{weak} experimental apparatus, showing the target, collimation, magnet coils and detectors for the eight identical octants of the spectrometer system. Incorporated in the apparatus is a tracking system to be used in ancillary measurements at very low beam current to map the Q^2 response of the detector system.*

The layout of the experiment is shown in Figure 2.1.2. A longitudinally polarized beam, a very high power liquid hydrogen target, a room temperature magnetic spectrometer

(QTOR), and a set of detectors for the scattered electrons at forward angles are the key elements of the experimental apparatus. The toroidal magnetic field focuses elastically scattered electrons onto a set of 8 rectangular quartz Cerenkov detectors coupled to photomultiplier tubes. The data is accumulated in current mode. A new high power cryotarget is under development for these measurements. The experimental asymmetry is –0.3 ppm. This will be measured to ±1.9% statistical and ±1.7 systematic errors.

Parameter	Value
Incident Beam Energy	1.165 GeV
Beam Polarization	80%
Beam Current	180 μA
Target Thickness	35 cm
Running Time	2200 hrs
Nominal Scattering Angle	9°
Scattering Angle Acceptance	±2°
Azimuthal Acceptance	67% of 2π
Solid Angle	ΔΩ=46 msr
Acceptance-averaged Q^2	0.03 $(GeV/c)^2$
Acceptance-averaged Physics Asymmetry	-0.29 ppm
Acceptance-averaged Experimental Asymmetry	-0.23 ppm
Integrated Cross-Section	3.7 μb
Integrated Rate (all sectors)	6.1 GHz
Statistical Error on the Asymmetry	1.9%
Statistical Error on $Q_{wp}=1 - 4\sin^2(\theta_W)$	2.8%

Table 2.1.1. *Kinematics, geometrical factors and running conditions for the Q_{weak} Experiment.*

The basic parameters of the experiment are summarized in Table 2.1.1. The main technical challenges result from the expected very small asymmetry and the required overall accuracy of ± 4%. The detector has been designed to accept electrons scattered at polar angles $\theta_e = 9 \pm 2$ degrees with an azimuthal acceptance as large as possible (8 quartz detectors with $\Delta\phi_e = \pm 15°$ each). Radiation hardness, insensitivity to backgrounds, uniformity of response, and low intrinsic noise are criteria that have been optimized in the detector design.

Controlling systematic errors is a very important part of this experiment. They are minimized by constructing a symmetrical apparatus, optimization of the target design and shielding, utilization of feedback loops in the source and beamline to control helicity correlated beam excursions, careful attention to beam polarimetry, and by carrying out ancillary measurement to determine the system response to helicity correlated beam properties and backgrounds.

The electron beam polarization must be measured with an absolute uncertainty in the 1-2% range. At present, this is done in Hall-C using an existing Moeller polarimeter. This can only be done for currents less than 10 μA. A major effort is underway to design and build a Compton polarimeter for this experiment. This polarimeter would allow continuous on-line measurement of the beam polarization at full current (180 μA) which is not currently possible.

Table 2.1.2 summarizes the statistical and systematic error contributions which we estimate for this measurement.

Error Contribution	Run I (23 days) $\Delta Q_{wp}/Q_{wp}$	Run II (93 days) $\Delta Q_{wp}/Q_{wp}$
Total Statistical	8%	2.8%
Systematic		
Helicity-correlated beam properties	0.6%	0.6%
Inelastic contamination	0.6%	0.2%
Hadronic corrections	2.0%	2.0%
Average Q^2 determination	1.0%	1.0%
Beam polarization	1.4%	1.4%
Target window background	<2.0%	<1.0%
Total Systematic	3.4%	2.9%
Total	8.7%	4.0%

Table 2.1.2. *Anticipated Statistical and Systematic Errors on Q_{wp}. Run 1 assumes 12 days of production data and 11 days of systematic studies. Run II shows the cumulative error after completing both runs. The final experimental error of ± 4% translates to a ±3% uncertainty in $\sin^2(\theta_W)$.*

2.1.4 Spectrometer

The spectrometer system consists of a cryotarget, collimator, magnet, and detector system. A downstream luminosity monitoring system will be used to control helicity correlated systematics. The schematic layout of the experiment is shown in Figure 2.1.3.

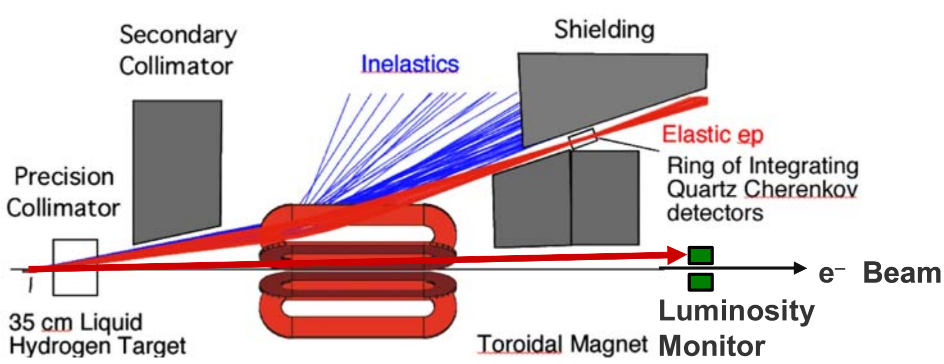


Figure 2.1.3. *Cutaway view of the experiment, showing the target, collimation, shielding, electron trajectories and detectors, for one of the eight identical octants of the spectrometer system.*

Elastically scattered electrons (red tracks) focus on the detectors while inelastically scattered electrons (blue tracks) are swept away by the toroidal magnetic field.

The experiment requires good separation of elastically scattered electrons from inelastic processes. Large acceptance is essential. To provide reasonable separation from neutrals requires that the elastic electrons be bent a minimum of about 10°. The required field integral is 0.67 Tm. A resistive toroidal spectrometer with 8-fold symmetry meets all these requirements. The coil geometry has been optimized in a series of simulation studies using GEANT plus numerical integration over the conductor's current distributions to determine the magnetic field. A simple racetrack coil design is adequate. The field calculations have been verified using TOSCA.

The coil design was carried out at MIT-Bates during this past year and we are now proceeding with conductor procurement. Construction of the coil will be by an outside vendor and managed by TRIUMF. MIT-Bates has responsibility for designing the magnet support structure, its construction and assembly. This effort will occur over the next two years.

The scattered electrons will be detected by eight long rectangular bars of quartz. The Cerenkov radiation is captured by a phototube at each end of the bar. The detector design is optimized to capture most of the elastically scattered background contributions. Since this is an integrating experiment, no separation of background electronically is possible. A Cerenkov detector minimizes sensitivity to low energy hadrons. Quartz also is very insensitive to radiation damage. Figure 2.1.4 shows a "Beam's eye" view with simulated GEANT events.

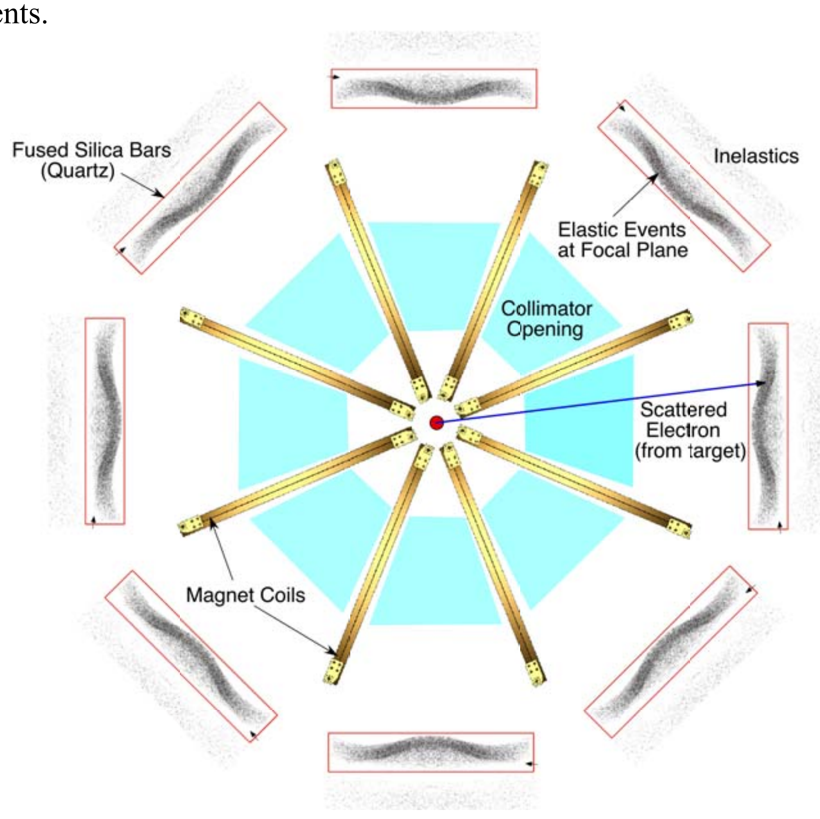


Figure 2.1.4. *"Beam's eye" view with simulated GEANT events. The magnet coils, primary collimator openings, and quartz detector bars are indicated. Elastic events are focused in θ and defocused in ϕ along the width and length of the detector bars, respectively. Inelastic events are deflected to larger angles, outside the detector boundaries.*

The cryotarget will be a major technical challenge for the experiment. Operating at a beam current of 180 μA and a length of 35 cm produces a heat load of 2.1 kW. This is much larger power than any currently operating LH_2 target anywhere. A preliminary engineering design shows that it should be possible to construct such a target while keeping helicity correlated density fluctuations at the required levels.

2.1.5 Compton Polarimeter

The beam polarization must be measured to an accuracy of 1-2%. It is very desirable to be able to do this continuously while the experiment is running and at full operating current. The present Hall-C Moeller polarimeter is limited to low currents and requires that the experiment is halted to make the measurement.

MIT physicists and post-docs are leading the design of a new Compton polarimeter for Hall-C. MIT has experience with such polarimeters both in the parity experiment at Mainz and with BLAST at Bates.

The Compton polarimeter takes advantage of the well understood properties of Compton scattering of circularly polarized photons with longitudinally polarized electrons. Operating at 1.2 GeV with an Ar-Ion laser (λ=514 nm) a 1% measurement can be achieved in 10 minutes. The low electron beam energy presents many challenges for the design. However, the Mainz polarimeter is designed for even lower energies, 855 MeV. It is now being commissioned.

We have completed the design of the 4-dipole magnetic chicane which is needed for the polarimeter. Detailed engineering drawings are now being prepared and procurement should occur within the next year.

A final decision still needs to be made on the best laser system. We are exploring the possibility of using a pulsed laser system which could have some advantages. It would probably preclude making a coincidence measurement of the recoiling photon and scattered electron. It would require very accurate knowledge of the energy response of the photon detector.

2.1.6 Experiment Status and Funding

Following initial PAC approval in 2002 and a successful technical review in January, 2003, a funding package to support the equipment construction totaling approximately

$3.4M US has been put in place, provided by Jefferson Laboratory, US DOE, NSF and NSERC in Canada. The breakdown of secured funding contributions for the equipment construction is summarized below, with a total (in US $) of $1.9M from DOE/JLab, $0.1M from LANL, $0.67M from NSF, $0.45M from US universities matching funds, and $0.26M from NSERC.

The beamtime for an 8% measurement denoted as "Run 1" in Table 2 was requested and approved at the January, 2002 PAC. The approach that has been taken by JLab management, who strongly support this experiment, is to work with the DOE to keep the total additional funds requested from the DOE below $2M, the cutoff scale, for an officially "Managed Project" at the DOE level. This has led to planning for an initial 8% measurement with all essential equipment unchanged from the 4% proposal goal, with the exception of the LH_2 cryotarget, which is currently funded to run at about 100μA.

2.1.7 Q-Weak Collaboration

The Q-Weak collaboration consists of more than 60 scientists from 17 institutions. The spokespersons are R. Carlini (JLab), J.D. Bowman (LANL), W.M. Finn (W&M), S. Kowalski (MIT), and S.A. Page (Manitoba). Major stakeholders will provide the polarized beam, the target, the beamline instrumentation, and required shielding; LANL leads the design and construction of the Cerenkov package and electronics; Louisiana Tech leads the efforts in computer simulations and building the forward GEM tracking detectors; MIT-Bates plays a major role in the design of the magnet coil package and design and construction of the spectrometer support stand as well as the Compton polarimeter; the Canadian collaboration (Manitoba, UNBC, TRIUMF) lead the coil construction project, and a consortium of US university groups including the College of William and Mary, Louisiana Tech, and Virginia Polytech University, have overall responsibility for the spectrometer calibration and particle tracking system. The funding/responsibility efforts are summarized in Table 2.1.3. The major stakeholders are represented by an Institutional Council, which is the decision-making body regarding policy issues for the experiment.

Subsystem	**Institution**	**Cost**	**Source**
Detectors/electronics	LANL	641.6	DOE/JLab 541.6, LANL 100
Target (Run 1)	JLab	280.7	DOE/JLab
QTOR Magnet: Cu, stand, infra:	MIT, JLab	600.8	DOE/JLab
QTOR Magnet: coil fabrication	Manitoba/TRIUMF	265	NSERC
Luminosity Monitor	VPI	50	NSF
Tracking system	US Univ.	1074.3	NSF 622.3, Univ. 452
Beamline/infrastructure	JLab	485.6	DOE/JLab
Total System		3398	

Table 2.1.3. *Costs and funding sources in US k$ for the Q_{weak} experiment construction. An average contingency of 19% is included in the total.*

Institution List:

Caltech, College of William and Mary, Hampton University, Jefferson Laboratory, Los Alamos National Laboratory, Louisiana Technical University, Mississippi State University, MIT-Bates, Ohio University, TRIUMF, Universidad Nacional Autoroma de Mexico, University of Connecticut, University of Manitoba, University of New Hampshire, University of Northern BC, and Virginia Polytechnic University.

Research Project		Total FTE		
		FY 06	FY 07	FY 08
QTOR (toroidal magnet)	Mech. Eng.	1	.5	0
	Elect. Eng.	.5	.5	0
	Designer	1.5	.5	0
	Tech.	6	2	0
Target Design	Physicist	.25	0	0
	Mech. Eng.	.5	.25	0
	Elect. Eng.	.25	.25	0
	Designer	.5	.25	0
	Tech.	.25	.25	0
Mini-Torus	Physicist	.25	0	0
	Mech. Eng.	.25	.25	0
	Elect. Eng.	.25	0	0
	Designer	.5	0	0
	Tech.	.5	0	0
Beam line hardware	Physicist	.5	0	0
	Mech. Eng.	.5	.25	0
	Elect. Eng.	.25	0	0
	Designer	.5	.5	0
	Tech.	.75	.5	0
Software/BAQ	Physicist	1	1	0
	Comp. Prog.	2	1	0

Table 2.1.4. *Summary of the manpower required for the* Q_{weak} *experiment.*

2.2 High-energy spin physics program at RHIC

B. Surrow, D. Hasell, R. Milner

2.2.1 Introduction

The Medium-Energy Group within the Laboratory for Nuclear Science at MIT is starting a new involvement at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) under the leadership of Professor Bernd Surrow within the STAR collaboration, which focuses on the collision of polarized protons to gain a deeper understanding of the spin structure and dynamics of the proton in a new, previously unexplored territory.

The first polarized proton run from December 2001 until January 2002 is the beginning of a multi-year experimental program which aims to address a variety of topics related to the nature of the proton spin such as: *i*) spin structure of the proton (gluon contribution to the proton spin, flavor decomposition of the quark and anti-quark polarization and transversity distributions of the proton), *ii*) spin dependence of fundamental interactions, *iii*) spin dependence of fragmentation and *iv*) spin dependence of elastic polarized proton scattering. A recent review of the RHIC spin program can be found in [2.2.1].

RHIC is the first accelerator to accelerate and collide polarized proton beams, ultimately at high luminosity and high polarization, at a center-of-mass energy of up to 500GeV. The key to maintain the transverse proton polarization through acceleration despite its large anomalous magnetic momentum, is to perform a rotation of the proton spin by 180º in the horizontal plane around a particular axis. This manipulation is performed by helical dipole magnets, known as 'Siberian snakes', which have been used for the first time at a proton collider. With two Siberian snakes installed in each ring, cumulative tilt effects of the proton spin are canceled, thereby eliminating the influence of depolarizing spin resonances. The Siberian snake magnets have been successfully commissioned during the first transverse polarized proton run. Besides the installation of Siberian snakes, the PHENIX and STAR experiments have been equipped with spin rotator magnets to allow for the precession from transverse to longitudinal polarization and thus to collide longitudinal polarized proton beams. The RHIC spin rotator magnets around the STAR and PHENIX interaction regions have been successfully commissioned in May 2003 which allowed colliding for the first time ever longitudinal polarized protons at a center-of-mass energy of $\sqrt{s} = 200\ \text{GeV}$.

Adequate time for the development of the polarized pp collider complex RHIC will be crucial to produce collisions of polarized protons with an anticipated design luminosity of 0.8 (2.0)$\cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$at $\sqrt{s} = 200\,(500)\,\text{GeV}$ and a beam polarization of 70%. A reasonable plan would involve RHIC running of 200GeV measurements in 2006-07 and 500GeV measurements in 2008-09.

During the period of 2004 - 2009, the major analysis goal of the new involvement within the Medium-Energy Group at the STAR spin program at RHIC is a comprehensive study of the protons spin structure and dynamics, in particular the nature of the QCD sea, using polarized protons. The centerpiece of this program is the measurement of the gluon contribution to the proton spin using various probes such as inclusive jet production, di-jet production and prompt photon production in the collision of longitudinal polarized protons. The completion and full exploitation of the STAR electromagnetic barrel and endcap calorimeter will be crucial for this analysis effort.

The second goal is the determination of the flavor-dependence of sea anti-quark polarization. A large unpolarized flavor asymmetry, $\bar{d} - \bar{u}$, has been measured by the E866 experiment [2.2.2]. Within the chiral quark soliton model based on a $1/N_c$ expansion, it is expected that the polarized flavor asymmetry, $\Delta\bar{u} - \Delta\bar{d}$, is larger than the already experimentally established flavor asymmetry in the unpolarized sector [2.2.3]. A measurement of the polarized flavor asymmetry will shed light into the underlying mechanism responsible for the expected polarized flavor asymmetry.

The production of $W^{-(+)}$ bosons provides an ideal tool to study the spin-flavor structure of the proton. $W^{-(+)}$ bosons are produced in $\bar{u} + d(u + \bar{d})$ collisions and can be detected through their decay to electrons (positrons), $e^{-(+)}$. Scattered $e^{-(+)}$ tagged in the STAR electromagnetic endcap calorimeter (EEMC) ($1 < \eta < 2$) off the incoming polarized proton beam moving toward (away) from the STAR EEMC, yield a purity for $W^{-(+)}$ coming from $\bar{u} + d(u + \bar{d})$ quarks of about 98% (75%). The separation of $e^{-(+)}$ from hadronic background will be important and therefore the full exploitation of the STAR electromagnetic endcap calorimeter (EEMC) with its intrinsic means for e/h separation (pre-shower and post-shower readout system) will be crucial. The discrimination of $\bar{u} + d \ (u + \bar{d})$ quark combinations requires distinguishing between high p_T $e^{-(+)}$ through their opposite charge sign which in turn requires precise tracking information. The p_T resolution of the STAR Time-Projection chamber (TPC) deteriorates rapidly for $|\eta| > 1$. An upgrade of the forward tracking system to distinguish the charge sign for high p_T charged $e^{-(+)}$ tracks is therefore needed which stems part of the STAR future upgrade effort which has been documented in the STAR Decadal plan [1.2.1]. This upgrade program forms the detector upgrade goal of the new involvement within the Medium-Energy Group at the STAR spin program and outlines the long-term analysis goal to measure the polarized flavor asymmetry, $\Delta\bar{u} - \Delta\bar{d}$. The tracking upgrade effort will be described in more detail in the next section.

The foreseen forward tracking upgrade at STAR to explore the expected polarized flavor asymmetry, $\Delta\bar{u} - \Delta\bar{d}$, will require to run RHIC at $\sqrt{s} = 500$ GeV at high luminosity. The STAR experiment will have to undergo a major upgrade of the data acquisition (DAQ) system to cope with the expected rate increase. This effort is closely linked to the upgrade of the STAR tracking system. The participation on this DAQ effort is foreseen at the level of engineering support by MIT-BATES in close collaboration to the STAR DAQ group which is headed by Dr. Tonko Ljubicic. Such participation would be crucial to keep a strong DAQ expertise at MIT-BATES for any future DAQ involvement at future experiments such as eRHIC. More details will be provided in the next section.

Supplementing the STAR electromagnetic Forward-Pion Detector (FPD) system ($3 < \eta < 4$) by additional calorimetery would allow more refined measurements on the mechanism responsible for the large measured transverse single-spin asymmetries, A_N, in forward π^0 production at RHIC at $\sqrt{s} = 200$ GeV [2.2.4]. The participation on this effort is foreseen at the level of engineering support by MIT-Bates which will be described in more detail in the next section.

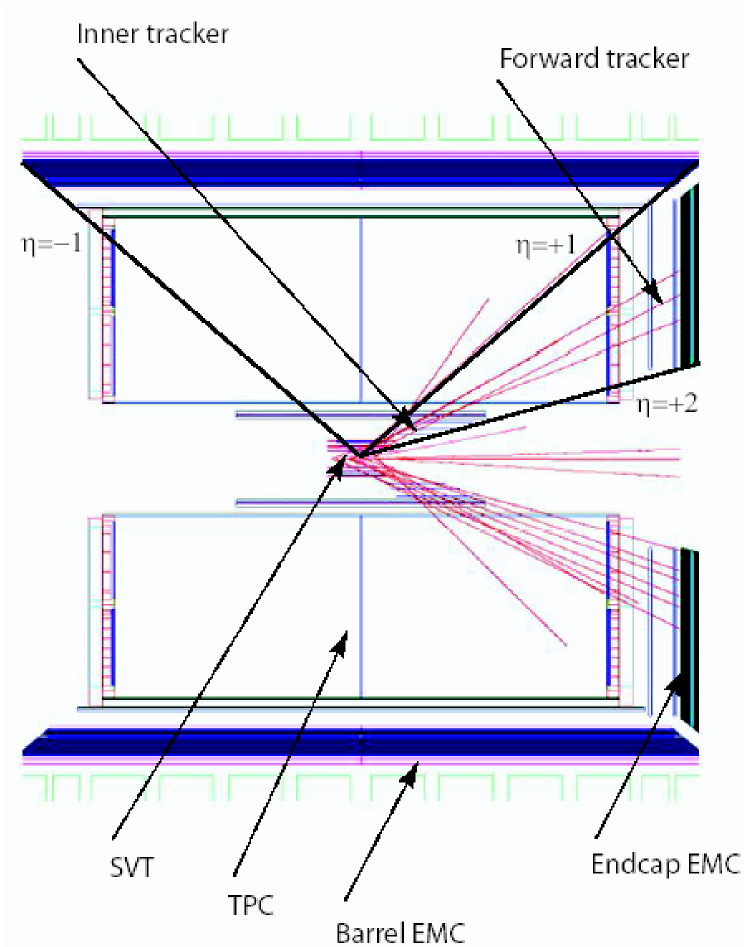


Figure 2.2.1. *First conceptual GEANT implementation of a new STAR forward tracking system ($1 < \eta < 2$) with new inner and forward tracking components.*

2.2.2 Tracking upgrade

2.2.2.1 Motivation

The resolution of the STAR Time-Projection Chamber (TPC) deteriorates rapidly beyond $|\eta| > 1$. It does not permit charge discrimination for high p_T $e^{-(+)}$ tracks. An upgrade of the STAR inner and forward tracking system is needed to provide the required tracking precision for $W^{-(+)}$ charge sign discrimination for high p_T $e^{-(+)}$ tracks. Such discrimination could be realized over the entire endcap region ($1 < \eta < 2$) with the addition of at least two space points at a distance of 1m (*inner space point*) and 2.5m (*forward space point*) from the STAR interaction point for up to 40GeV/c $e^{-(+)}$ tracks provided that those space points are measured with a precision of at least 100μm.

Figure 2.2.1 shows a first conceptual implementation using the GEANT detector simulation framework of an inner and forward tracking system. The requirements on those tracking components are a precise intrinsic hit determination at the level of at least 100μm, fast intrinsic timing response and minimal dead material. Those demands for the STAR tracking upgrade would make silicon and GEM-type tracking detectors a natural choice. The inner tracking upgrade has been laid out in the first GEANT detector simulation as shown in Figure 1 by silicon detector layers whereas the large-area tracking area in front of the STAR EEMC is based on a GEM-type tracking detector.

It is foreseen to consider those detector technologies in the design of the tracking system and strongly engage with several MIT faculty and staff members in collaboration with other STAR institutes in this effort. This would therefore make use of the existing (LNS silicon laboratory) and proposed (Micro-pattern detector facility) detector facilities at MIT. Physics simulations and detailed studies on the detector layout are underway.

2.2.2.2 Utilization of MIT-BATES infra-structure

The following provides an outline of the usage of the MIT-BATES infra-structure and personnel for the period of FY05 and FY06-FY08.

- Conceptual design of the STAR GEM tracker together with 1 MIT-BATES staff physicist starting in FY05 in collaboration with other STAR institutes
- Mechanical design of the inner and outer tracking system starting in FY05
- Silicon sensor testing and characterization, module assembly and bonding could be carried out by the existing LNS silicon laboratory (FY06-FY08)
- GEM-foil testing, inspection and final GEM tracker module assembly could be carried out in the proposed MIT-BATES micro-pattern facility (FY06-FY08)
- Final integration and test of the GEM tracker in a larger clean construction area of at least 1000 sq. feet in size (FY06-FY08)

The following requirements on personnel and infra-structure are foreseen:

- 1 staff physicist to engage in the conceptual design of the STAR GEM tracker starting in FY05
- Micro-pattern facility including staff (FY06-FY08)
- LNS silicon facility including staff (FY06-FY08)
- 1 staff physicists to coordinate local design and construction efforts (mechanical integration and DAQ) (FY06-FY08)
- 1 mechanical engineer for mechanical design including support by

- technicians (2) for detector assembly (1) and final integration (1) and availability of mechanical and electronics workshops (FY06-FY08)
- Clean workspace with crane support (no clean room requirement) for final integration and testing

This detector design and construction effort for the STAR tracking upgrade will provide an ideal learning environment for undergraduate and graduate students and a stimulating research facility for future research associates. This effort will allow MIT with its existing (LNS silicon laboratory) and proposed facilities (Mirco-pattern detector facility) to play a leading role in the STAR tracking upgrade program.

2.2.3 STAR Forward calorimeter upgrade

2.2.3.1 Motivation

Besides studying the spin properties of the QCD sea at RHIC, the measurement of single transverse spin asymmetries, A_N, have created recently a lot of attention with the first measurement of A_N for leading π^0 production from colliding polarized protons at $\sqrt{s} = 200\ \text{GeV}$, $x_F \approx 0.2\text{-}0.6$ and $p_T \approx 1\text{-}3\text{GeV}$ [2.2.4]. These unexpectedly large values for A_N have been obtained by the E704 experiment at FNAL at $\sqrt{s} = 20\ \text{GeV}$ [2.2.5]. Those measured effects cannot be explained within the conventional framework of QCD ignoring quark masses and employing a leading-twist and collinear approximation which has been successful in several applications of QCD.

Qiu and Sterman have shown that these large values of A_N can be understood as a higher-twist perturbative QCD effect [2.2.6]. Other models, involving e.g. intrinsic $k_\perp$ dependence in the initial (Sivers) [2.2.7] and final state (Collins) [2.2.8], have also attempted to explain the E704 data, and make similar predictions for A_N at RHIC energies. The Collins effect would allow a means to access the transverse parton distributions folded with a chiral-odd Collins fragmentation function.

The mechanism by Collins would predict an azimuthal dependence of the produced forward π^0 with respect to the jet axis. The objective would be to measure the hadronic and electromagnetic components of the forward jet energy. With the jet direction measurement, the angle the pion makes with respect to the jet axis (Collins angle) could be determined [1.2.1]. Such measurements could be helpful to identify the mechanism for transverse single spin asymmetries.

The observation of high p_T hadron suppression in d-Au collisions in the forward direction has received considerable attention with preliminary results presented by the Brahms collaboration [2.2.9] This could be accounted for by saturation phenomena as formulated within the Color-Glass Condensate model [2.2.10] which is one of the prime physics motivations of the future e-Au program at eRHIC. An upgrade of the STAR forward calorimeter system would allow to explore this interesting kinematic region in Au-Au/d-Au collisions in comparison to pp collisions.

The participation on this forward calorimeter effort is foreseen at the level of engineering support by MIT-BATES which will be described in more detail in the next section.

2.2.3.2 Utilization of MIT-BATES infra-structure

Figure 2.2.2 shows a top and side view of the EAST tunnel platform inside the STAR experimental hall. A symmetric platform (WEST) is installed on the other side of the

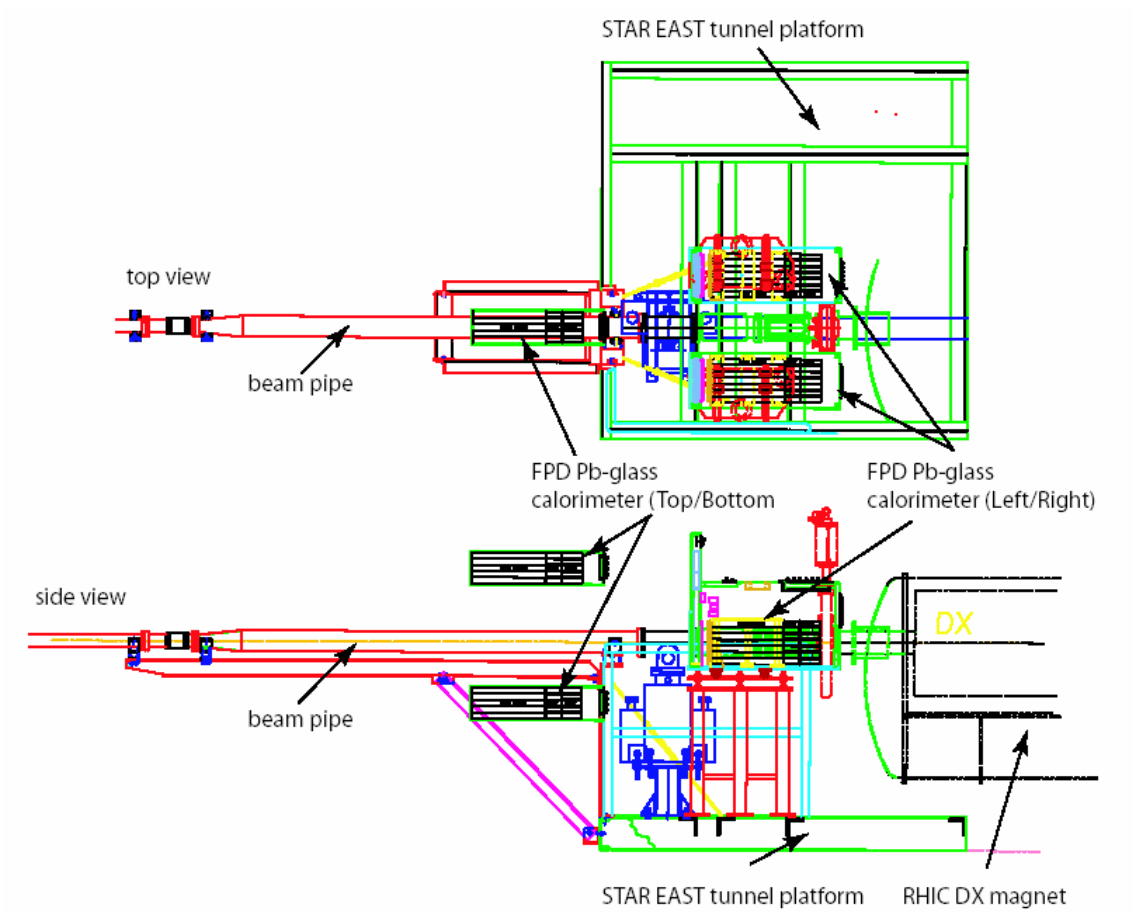


Figure 2.2.2. *East platform extension of the RHIC tunnel inside the STAR experimental hall. The top-view and side-view figures show the location of the beam pipe, the Pb-glass forward pion detector modules relative to the DX magnet.*

STAR interaction region. The location of the platform, the beam pipe, the RHIC DX magnet and the FPD Pb-glass calorimeter (Left/Right) is shown. Supplementing this setup by additional calorimetry will require an extension of the existing platforms to free up space between the current FPD Pb-glass calorimeter (Left/Right) and the RHIC DX magnet. In addition, a support structure for additional calorimetery on top of the platform will be necessary.

The following provides an outline of the usage of the MIT-BATES infra-structure and personnel for the period of FY05 and FY06:

- Mechanical design and construction the STAR EAST/WEST platform extension and support structure for additional calorimetry

The following requirements on personnel and infra-structure are foreseen:

- 0.5 mechanical engineer for mechanical design including support by
- 1 technician and availability of a mechanical workshop (FY05-FY06)

2.2.4 STAR Data Acquisition Upgrade Project

2.2.4.1 Motivation

The STAR Data Acquisition Upgrade Project ('DAQ1000') which is headed by Dr. Tonko Ljubicic is one of the proposals in the STAR Decadal Plan document [1.2.1]. The main goal of this project is the increase of the data-taking rate of STAR (In particular the STAR TPC, being the detector with the largest data volume) by more than an order of magnitude. The proposed final rate is projected to be above 1000 Hz thus maintaining a large event throughput while at the same time providing a much smaller dead time for the benefit of rare processes.

The STAR Upgrade Plan envisions the start of construction of this DAQ upgrade to be around FY06-FY07, depending on the budget profile, the progress of the ongoing R&D effort as well as the availability of R&D funds until then.

The STAR Data Acquisition Group has already started an R&D effort aimed at providing the architectural design. This is expected to be followed by prototype modules until FY05. It is foreseen that by the end of FY05 an electronics circuit board ('DAQ Receiver Board') will be produced in prototype quantities and will be fully tested and ready for production.

This DAQ Receiver Board will contain sophisticated electronics such as large FPGAs and potentially DSPs and/or CPUs to be able to handle the computationally demanding task of 2-dimensional peak finding and data compression in the TPC as well as other STAR detectors. The board will feature a state-of-the-art optical fiber I/O as well as the then-current computer system interface (i.e. PCI Xpress or similar). Its complexity is assumed to be greater than a full featured standalone computer as of today. The number of these boards is expected to be between few hundred and a thousand (depending on the cost/size ratio at the time of production). The total production is expected to be at the level of 1-2 M$.

2.2.4.2 Utilization of MIT-BATES infra-structure

The resources and expertise at MIT-BATES make a participation in connection with the STAR tracking upgrade effort a real opportunity to maintain a high-level of DAQ expertise with the construction phase of the STAR DAQ1000 project and thus to engage into DAQ systems at the RHIC collider environment. This has clear benefits for the long-term plans at eRHIC.

The following provides an outline of the usage of the MIT-BATES infra-structure and personnel for the period of FY06-FY08:

- Participate in the production, testing, verification, debugging and possible repair of the full complement of the STAR DAQ upgrade receiver boards

- Handle procurement and other issues with off-site manufactures

- Participate in the installation process and in-situ testing at the STAR detector at Brookhaven National Lab once the receiver boards are fully verified.

The following requirements on personnel and infra-structure are foreseen (FY06-FY08):

- 0.5 digital electronics engineer with experience in PCB board manufacturing and processing as well as debugging techniques and

- 1 electronics technician who would help in the process of testing and debugging

- 0.5 DAQ/embedded system programmer who would take part in the development of the software bench which will be used in the testing and verification stage

It would be beneficial if such an engineer and programmer be identified even at this current early stage of the Project (FY05) who would then participate in design meetings and be partly involved throughout the design process and thus become familiar with the final product before it moves into the production stage.

Due to the early stages of the DAQ1000 project one should keep in mind that the above estimates are preliminary.

2.3 Micro-pattern detector facility at MIT-BATES

B. Surrow, U. Becker and P. Fisher

2.3.1 Introduction

Gaseous detectors in particular multi-wire proportional chambers (MWPC) introduced by Georges Charpak in 1968 at CERN [2.3.1] have a long tradition and are widely used in nuclear and particle physics as position-sensitive devices. Other areas of their successful application include astrophysics, medical diagnostics and biology [2.3.2]. The invention of the MWPC has been awarded by the Nobel Prize of Physics in 1992.

After its first introduction, the MWPC concept has been applied and extended to various detector configurations such as drift chambers, time projection chambers and time expansion chambers [2.3.3-2.3.6]. Despite continued improvements in their performance characteristics, the granularity and rate capabilities turned out to be limiting factors in particular for high luminosity applications in nuclear and particle physics.

In order to overcome those performance limits, a "second generation of gaseous detectors" was introduced which promised to be superior in terms of granularity and rate performance. The micro-strip gas chamber (MSGC) was first described by A. Oed in 1988 [2.3.7]. It consists of tiny metal strips over a thin glass substrate, which form an alternate structure of anode and cathode strips. The basic underlying principle is similar to that in case of a multi-wire proportional chamber. However, the application of photolithographic techniques allowed to manufacture rather fine structures which resulted in a substantial improvement in granularity. Furthermore, the problem of space charge build up, which is one limiting factor for multi-wire proportional chambers in a high rate environment, is reduced due to the ability for fast positive ion collection. This provides a higher rate capability. This "second generation of gaseous detectors" is usually referred to as "micro-pattern detectors". A review of their development and application can be found in [2.3.8].

Despite those promising features, their long-term and high-rate performance revealed several weaknesses. Under sustained radiation, polymerization processes lead to the deposition of an insulating layer on the metal anode and cathode strips and thus degraded the performance. Discharge effects due to large energy losses for example by heavy ionizing particles have shown to potentially lead to permanent damage of the metal strips.

In order to overcome those limitations, several solutions have been suggested some of which are by now employed in several running experiments in nuclear and particle physics. The "Compteur à Trous" (CAT) is based on avalanche multiplication in narrow holes [2.3.9]. The MicroMeGas concept uses a narrow gas parallel plate multiplication [2.3.10]. The Gas-Electron Multiplier (GEM) idea exploits a thin insulation foil, metal-clad on both sides, which is perforated by a regular dense hole pattern [2.3.11].

It is in particular the application of the GEM-type tracking detectors, which promises to have a widespread usage at future high-luminosity nuclear and particle physics experiments. The COMPASS experiment at CERN is successfully operating 20 triple

GEM detectors [2.3.12]. The design, construction and in particular the manufacturing of GEM foils for those detectors has been carried out at CERN. An outstanding issue in the application of GEM-type tracking detectors is the commercial manufacturing of GEM foils. Several academic institutions are actively involved in establishing such a process.

Micro-fabrication techniques, new materials and manufacturing methods recently developed in the field of Micro-Electro Mechanical Systems (MEMS) are presently experiencing an enormous boost. The application of MEMS technology in the design of novel gas detectors promises to further enhance the performance of micro-pattern detectors.

Several groups within the Laboratory for Nuclear Science at MIT are strongly pursuing GEM-type tracking detectors at future experiments such as for the STAR tracking upgrade, the eRHIC tracking system and detector systems at other future collider facilities. Those efforts will require a clean room laboratory to handle, inspect and test GEM-foils besides the actual detector assembly. Such a micro-pattern detector facility is not available as of now. MIT-Bates laboratory is an ideal location to pursue such a facility with its tremendous resources of highly skilled staff and infra-structure to carry out a complete GEM-type tracking detector construction effort from the test and assembly of individual GEM detector modules to the final integration into a larger detector structure. This led to the proposal to establish a micro-pattern detector facility at MIT-BATES together with the appointment of a research physicist with demonstrated strong leadership skills in micro-pattern detector development to focus on the advancement of this promising tracking technology.

MIT-BATES laboratory would provide a foundation to establish a close cooperation between academic institutions and industry to conduct R&D work on micro-pattern detectors in particular GEM-type tracking detectors including their actual assembly and testing.

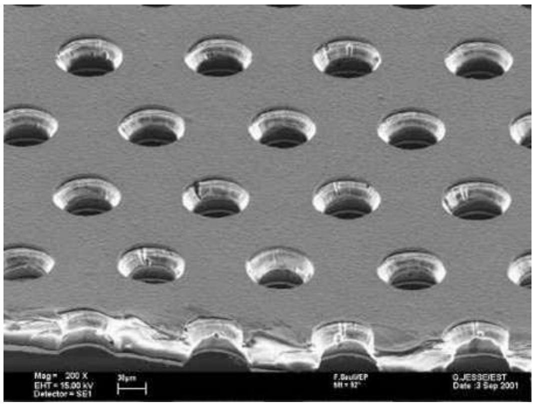
A micro-pattern facility at MIT-BATES has enormous educational benefits. It will provide an ideal learning environment for undergraduate and graduate students and a stimulating research facility for future research associates at the forefront of future detector R&D and construction efforts in an academic environment. It will allow to provide the means to attract and retain the best young people for an active and exciting research program.

This is a unique opportunity for MIT-BATES laboratory within the US nuclear and particle physics community since such efforts have so far been concentrated outside the US.

The proposal starts with a brief overview of the GEM tracking detector concept followed by an overview of current R&D activities and future applications. The layout including a cost estimate for the clean-room setup, equipment and personnel is presented at the end.

2.3.2 Micro-pattern tracking detector concept

Several new concepts of novel gas ionization detectors have been presented. An overview can be found in [2.3.13, 2.3.14].



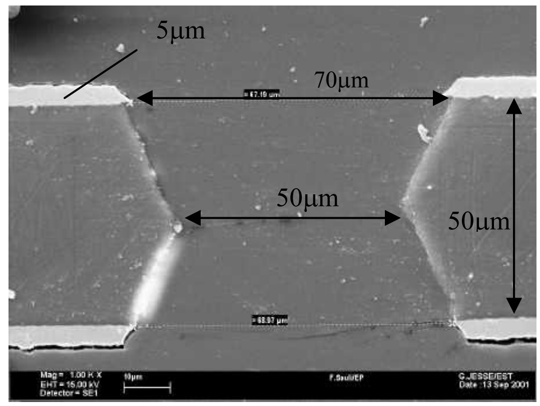


Figure 2.3.1. *Electron microscope picture of a GEM foil (left) and cross-section view through one hole (right).*

Gas Electron Multiplier (GEM) [2.3.11] and MicroMeGas [2.3.15], two types of micro-pattern activities to overcome the limitations of micro-strip gas chambers (MSGC), have been extensively studied.

A GEM is made by a thin (50μm) Kapton foil, which is metalized from both sides by a ~5μm layer of copper each with a large number of microscopic holes of ~70μm diameter at a pitch of ~140μm. An electron microscope picture of a GEM foil is shown in Figure 2.3.1 (left). A detailed cross-section view of a single hole is shown in Figure 2.3.1 (right), which clearly shows a double-conical shape as a consequence of the chemical etching process. The GEM manufacturing technique was developed by the CERN-EST-DEM workshop. The process starts with the production of two identical masks whose pattern is transferred to the foils, which are coated by a photosensitive layer by means of conventional printed-circuit board technology exposing the coated layers to UV light. This process is followed by chemical etching of the copper cladding and the Kapton itself. Upon inserting the GEM foil between a cathode and a read-out anode and application of a voltage between the two sides (~300-500V), electrons released in the upper gas volume drift into holes, multiply (E ~ 50-100 kV/cm) and transfer to the lower side where they can be collected or further amplified. The simulated field configuration inside a GEM hole is shown in Figure 2.3.2 [2.3.13]. Almost all ions, which are created in the holes, are quickly collected. The signal is generated by electron collection at the readout plane with the ion response effectively shielded by the closest GEM electrode, which provides therefore fast timing characteristics that allows its usage in a high-rate environment. A unique feature of this device is that the charge multiplication is electrically separated from the readout. This offers a wide freedom in the choice of the readout pattern, which can be realized using strips or pads all at ground potential. Gas amplifications can be obtained up to 10^3 in a wide range of operating gases and conditions, including strong magnetic fields [2.3.16]. Several GEM foils can be cascaded that allows to reach a higher gas amplification and at the same time significantly reduces the problem of discharges in the presence of heavily ionizing particles. Gas multiplications at the level of 10^6 have been demonstrated by a triple-GEM foil detector for the COMPASS experiment [2.3.12].

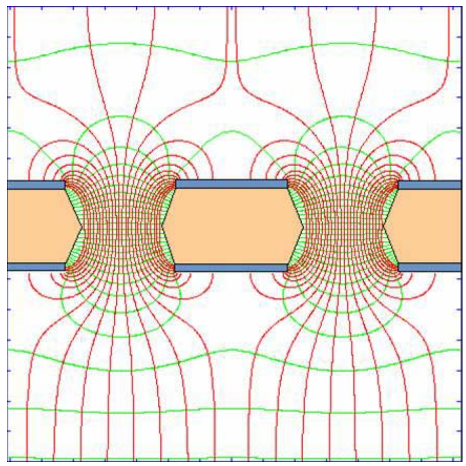


Figure 2.3.2. *Simulated field configuration inside a GEM hole [2.3.13]. Electrons released in the upper gas volume drift into holes, multiply and transfer to the lower side where they can be collected or further amplified.*

A detailed description of MicroMeGas detectors can be found in [2.3.15, 2.3.17, 2.3.18]. It is a two-stage parallel plate electrode gas detector, where a low-field, few mm thick conversion/drift volume is separated from a 50-100μm thick amplification gap (E~30-50kV/cm) by a thin metal micromesh-type grid. A schematic cross section view of the COMPASS MircoMeGas detector is shown in Figure 2.3.3. Electrons, which are created in the conversion gap, drift into and initiate an avalanche in the amplification gap and are collected by the readout structure whereas positive ions are collected by the grid. This gives rise to a rather fast timing response and thus its application in a high-rate radiation environment. The micromesh is made of 4μm thick Ni or Cu grids with 200-500 lines per inch. The needed parallelism between the micromesh grid and the anode is maintained by cylindrical spacers of 100-150μm diameter, and placed every ~2 mm. Those are printed on a thin substrate together with a readout structure by conventional lithography of a photo-resistive polyamide film. The thickness of the film defines the amplification gap. This is a simple process that allows the construction of large detectors with good uniformity and energy resolution over the whole surface. MicroMeGas detectors are more sensitive to discharge problems compared to GEM detectors but robust against permanent damage. The position resolution has been measured to be at the level of 12μm [2.3.19]. A timing resolution of 4.5ns has been presented in [2.3.20].

Both variants, MicroMeGas and GEM, represent a rather cost effective solution compared to silicon-based position sensitive detectors when position resolution for large-area tracking detectors in the range of 30µm to few mm is required in particular operating in a high-rate environment.

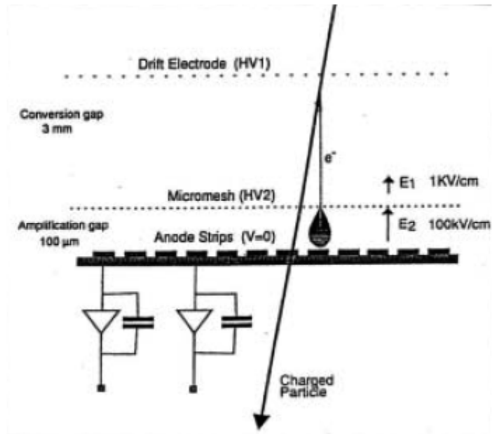


Figure 2.3.3. *Schematic cross section view of the COMPASS MircoMeGas detector [2.3.21].*

2.3.3 R&D activities and micro-pattern detector utilization

2.3.3.1 Overview of R&D activities

Micro-pattern detectors have been extensively studied in recent years and are currently used as tracking devices in particular in high rate experiments. Current R&D activities are concentrated to optimize structure and operating parameters both for tracking detectors and TPC readout systems.

The main arguments to employ GEM and MicroMeGas type tracking detectors are as follows:

- Fast and “narrow” signal, dominated by electron collection with negligible “ion tail”
- Ion feedback suppression to TPC drift volume
- High precision in position reconstruction
- Staged amplification setups (Double and triple-type GEM detectors)
- Operation with different gases inside strong magnetic fields
- Simple “mechanical” construction, without the need for wire tensioning
- Small thickness and low material budget
- Flexible foil and read-out geometry
- Low distortions due to **E** x **B** (in amplification region)
- Applications in combination with other detector systems (TPC, RICH)

The most impressive example of micro-pattern detector utilization is the COMPASS experiment at CERN [2.3.36]. A system of 20 large size triple-GEM detectors and 6 MicroMeGas detectors have been built as part of the high-rate tracking system at COMPASS.

Each GEM based detector has an active area of 31x31cm^2. Each detector provides a two-dimensional projective strip read-out at a pitch of 400μm. Good time (~15ns) and position (~40μm) resolution have been achieved. A cluster charge correlation between two orthogonal read-out strip projections offers a powerful tool for multi-track reconstruction. After the installation of the triple GEM detectors inside the COMPASS experiment, none of the readout channels were lost and the detector performance is stable since then. A description of the construction and performance of the COMPASS GEM detector system will be provided in the next section.

The MicroMeGas detectors built for the COMPASS experiment have a 40 x 40 cm^2 active area and are operated in a gas mixture of Ne-C_2H_6-CF_4 (80-10-10) with 360-420μm pitch strip read-out. A discharge rate of less than 0.1/spill was observed in the high-intensity muon beam of COMPASS. A time resolution of ~10 ns has been reached.

Several R&D activities are concentrated to study different configurations for TPC readout systems on the basis of micro-pattern approaches [2.3.22, 2.3.23, 2.3.24], which are very promising. GEM foils have been used in combination with photo-converters to demonstrate the possibility to construct a “gas photo-tube” [2.3.25,2.3.26]. The GEM application with a “reflective” CsI coating on top of the “first” GEM foil can be used as a large size detector with high efficiency to UV-photons [2.3.27].

One of the most urgent needs is to find a company or laboratory to establish a GEM foil mass-production. So far, high-quality GEM foils have been only produced at CERN by the CERN-EST-DEM workshop. Besides that, the setup of a micro-pattern facility is urgently needed to advance on micro-pattern detector R&D, test and construction, in particular within the US nuclear and particle physics community. With such a facility, MIT-BATES laboratory is expected to play a leading role in establishing a close cooperation between academic institutions and industry to conduct R&D work on micro-pattern detectors in particular GEM-type tracking detectors. This provides a unique opportunity for MIT-BATES laboratory where several research groups at MIT are actively pursuing the application of GEM-type tracking detectors for future nuclear and particle physics experiments. An overview of those activities will be given in section 2.3.4.

A micro-pattern facility at MIT-BATES would also allow to advance on the application of new materials in the design of novel gas detectors besides the main activity of handling, inspecting and testing GEM-foils to be used for various GEM-type tracking detector applications. Several novel materials have recently become available for the fabrication of “microstructure” devices, the most important of which is the material known as SU-8. SU-8 is a photo-patternable epoxy-based dielectric material originally developed for the microelectronics industry to provide a high-resolution negative imaging resist for use in the fabrication of advanced semiconductor devices [2.3.29]. The resist has several attributes which make it suitable for micromachining applications and therefore prompt its consideration for microstructure radiation detector fabrication. An early attempt to improve gas detector performance for x-ray imaging using micro-fabrication techniques with photo-patternable technologies and new materials was reported in [2.3.28].

An innovative technique, the ion trap [2.3.30], employs new materials and MEMS fabrication methods. This design promises a fast signal response due to rapid ion charge evacuation, low space charge build up and low ion feedback suitable for applications in TPC and gaseous photomultipliers.

2.3.3.2 COMPASS experience with a triple-GEM detector

Introduction

The COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) experiment at CERN is a new fixed target experiment which is in operation since 2001. It is designed to explore the nucleon spin structure and spectroscopy of hadrons. The first goal of the experiment is to explore the gluon contribution to the nucleon using open charm production in the photon-gluon fusion process and the production of high p_T hadron pairs from deep inelastic scattering of polarized muons on polarized nucleons.
This program requires high intensity muon and hadron beams of $2 \cdot 10^8$ muons of 160GeV per 5s spill, and 10^8 p, K and π per spill at 100-280GeV from the Super Proton Synchrotron (SPS). This sets stringent requirements on the high-rate and multi-track resolution capability. It requires fast, dead-time free readout electronics and low material budget to reduce multiple scattering.

The COMPASS tracking system

The tracking system is realized by various detector systems with increasing rate capability going closer to the beam axis where the particle flux is highest.
The region between 2.5-3.0cm of radial distance from the beam region is laid out by a set of silicon micro-strip detectors and scintillating fiber detectors.
The intermediate tracking region spans a radial distance of approximately 2.5cm to 40cm. Micro-pattern detection systems have been used for this tracking region. The area in front of the first momentum-analyzing magnet (SM1) comprises three stations of MicroMeGas. Each station is made out of 4 planes with horizontal (X), vertical (Y) projections, and two projections inclined by ±45° (U,V). The area downstream of the first momentum-analyzing magnet (SM1) is laid out by 10 GEM stations. Each GEM station is comprised by two GEM detectors which are rotated by 45° with respect to each other.
The average particle rate per strip for a GEM detector is expected to be around 30-40kHz with a maximum of up to 150kHz close to the beam axis. Those high rate requirements together with the demand for large area tracking capability, high spatial resolution and low material budget has been realized with the installation of 20 large-size (31 X 31cm^2) GEM detectors.

The COMPASS triple-GEM tracking detector

A) Layout

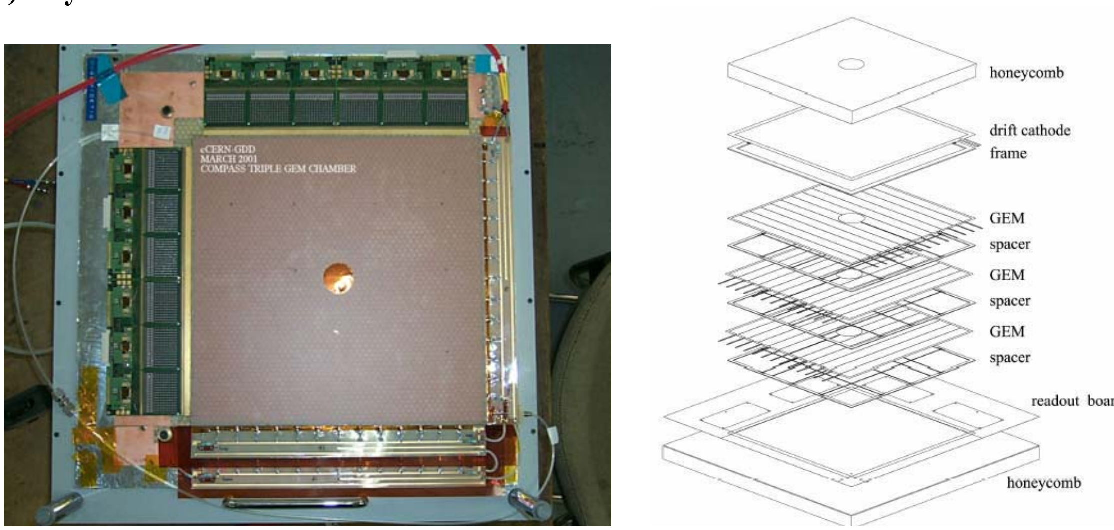


Figure 2.3.4. *Completed triple-GEM detector including HV distribution and two-dimensional readout electronics. The active area amounts to 31 X 31cm^2 (left). Exploded view of the triple GEM-detector (right) [2.3.36].*

A completed COMPASS triple GEM detector is shown in Figure 2.3.4 (left). An exploded view is shown in Figure 2.3.4.

The top part is a honeycomb plate followed by the drift electrode, three GEM foils and the readout board, which is attached to the lower honeycomb plate. The drift cell is 3mm thick whereas all other cells have a thickness of 2mm. Each cell is separated from each other by fiberglass strips, which have a width of about 400μm, which introduces only a small local efficiency loss.

The readout board is realized by a two-dimensional projective read-out of the signals, which makes use of a printed circuit board with two layers of perpendicular copper strips at 400μm pitch, which are separated by 50μm thick Kapton ridges. Each coordinate has 768 readout strips.

B) Readout electronics

The readout electronics is based on the APV25 chip [2.3.34] which is a 128-channel amplifier-shaper ASIC with an analogue pipeline of 192 cells for each input channel. This chip is based on the 0.25μm CMOS process which provides clear advantages in power consumption, noise performance and radiation tolerance. The amplified and shaped signals are sampled at a rate of 40MHz and stored in a pipeline with a latency of up to 160 clock cycles (4μs).

C) Assembly

The assembly of the GEM detectors is entirely carried out in a clean room of at least class 1000 with temperature control and low moisture level (~40%). Protective clothing is always worn. A schematic overview of the clean room where the COMPASS GEM detectors were assembled is shown in Figure 2.3.5. The construction of the GEM detectors for the COMPASS experiment including a detailed description of the infrastructure, materials, procedure and quality requirements can be found in [2.3.31].

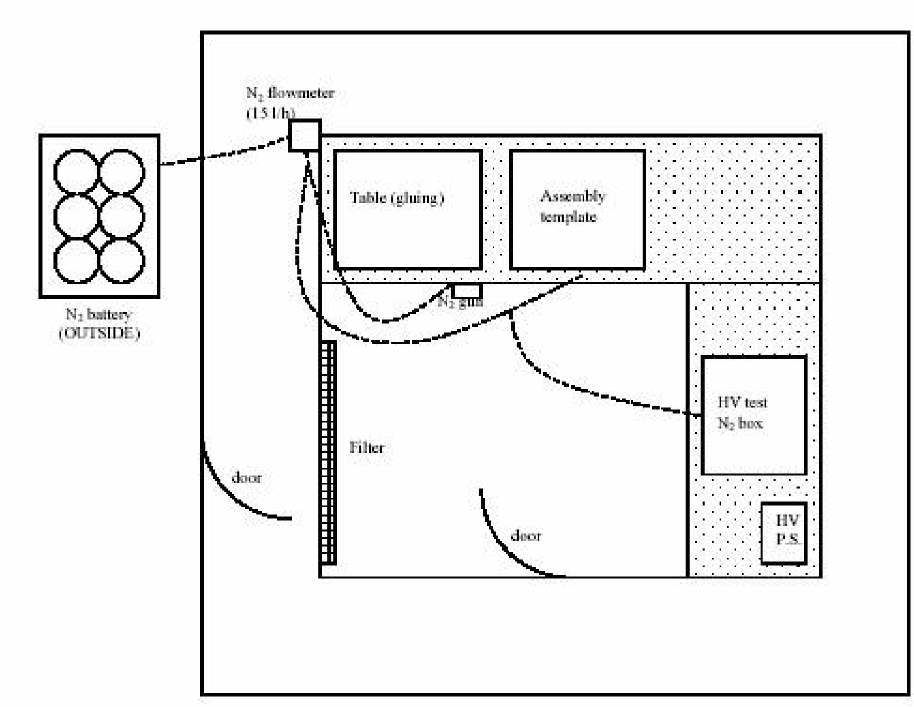


Figure 2.3.5. *Schematic layout of the COMPASS clean room setup [2.3.36].*

D) Performance

The following section provides a brief account of the main performance features of the COMPASS triple GEM detectors [2.3.36]. Prior to the assembly of a GEM detector, each GEM foil is inspected and tested. First quality checks are performed before a foil leaves the GEM production facility such as a measurement of the resistivity in air between the conductive GEM sides, which has to exceed 2GΩ to be accepted. Once a GEM foil is accepted and ready to be taken to the actual GEM detector assembly facility it is placed in clean packing and left in clean storage units if necessary.

The HV characteristic is repeatedly checked during the whole assembly operation, i.e. before mounting and during various assembly steps. This procedure is carried out in a nitrogen filled box.

It has been shown that a triple GEM detector can be safely operated over a wide operating range. The discharge probability is hardly measurable. Several foils thus allow to sustain large gain values even in the presence of heavy ionizing particles [2.3.36].
It has been shown in [2.3.32] that a $10x10cm^2$ double GEM prototype detector is less sensitive to aging than other micro-pattern gas detectors. The COMPASS triple GEM detector was tested for aging effects by irradiating the detector using a beam of 8.9keV X-rays for about one month at rates of up to $2.5 \cdot 10^4 Hz/mm^2$. No gain loss was observed even after collecting more than $7mC/mm^2$, which corresponds, to the total charge of seven years of operation in the expected COMPASS radiation environment [2.3.35].
Three triple GEM detectors were tested in a test-beam experiment at the T11 beam-line of the CERN PS. The detectors were exposed for several weeks to a 3.6GeV charged particle beam of about 10^6 particles per 200ms spill. A silicon micro-strip detector provided an independent position measurement.

Taking into account the accuracy of the silicon micro-strip detector of approximately 15µm and deteriorating effects from multiple scattering, a position resolution of 40µm has been established which agrees with previous prototype measurements [2.3.33]. Efficiencies in excess of 98% are achieved for the actual active area.

The time resolution of the triple GEM detector has been determined to be 15.2 ± 0.1ns during the test-beam experiment. This value represents a convolution of physical and electronic effects compared to the intrinsic resolution of about 7ns rms [2.3.33].

A set of 20 triple GEM detectors is in operation as an integral part of the COMPASS experiment. The performance of those novel new tracking devices so far have clearly shown that they meet the requirements for tracking devices in modern high-energy physics experiments in terms of their rate capabilities, timing characteristics, position resolution and tracking efficiency.

2.3.4 Future GEM tracking application

Tracking detectors on the basis of micro-pattern gaseous detectors promise to have a wide variety of applications at future nuclear and particle physics experiments in particular in a high-rate environment. In addition, applications for medical diagnostics and biology seem feasible.
The following sections provide three examples for future applications of GEM-type tracking detectors, which are strongly pursued by several groups within the Division of Nuclear and Particle Science at the Department of Physics at MIT.

2.3.4.1 STAR

The high-energy spin physics program at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) which focuses on the collision of polarized protons to gain a deeper understanding of the spin structure and dynamics of the proton in a new, previously unexplored territory has been discussed in section 2.2.

The production of $W^{-(+)}$ bosons provides an ideal tool to study the spin-flavor structure of the proton. $W^{-(+)}$ bosons are produced in $\bar{u}+d(u+\bar{d})$ collisions and can be detected through their decay to electrons (positrons), $e^{-(+)}$. The discrimination of $\bar{u}+d$ $(u+\bar{d})$ quark combinations requires distinguishing between high p_T $e^{-(+)}$ through their opposite charge sign which in turn requires precise tracking information. The tracking precision for $1.0 < \eta < 2.0$ of the STAR Time-Projection Chamber (TPC) is rather poor. An upgrade of the forward tracking system to distinguish the charge sign for high p_T charged $e^{-(+)}$ tracks is therefore needed which is part of the STAR future upgrade effort which has been documented in the STAR Decadal plan [1.2.1].

Such a forward tracking system requires operation in the expected high-luminosity environment at RHIC ($2 \cdot 10^{32} cm^{-2} s^{-1}$ at $\sqrt{s}$=500GeV). The forward tracking area to be covered in front of the STAR Electromagnetic Endcap Calorimeter (EEMC) amounts to ~$10 m^2$. The charge sign discrimination of high p_T $e^{-(+)}$ tracks from $W^{-(+)}$ requires high precision. First simulation results have shown that a position accuracy of at least 100µm is needed. A GEM-type forward tracking detector constructed by smaller individual tracking chamber units based on for example triple-GEM chambers promises to fulfill the demands on such a new large-area forward tracking system for the STAR experiment.

This effort relies on the availability of a micro-pattern clean room facility to handle and test GEM foils and assemble individual GEM-type chambers. More details on the utilization of the MIT-BATES infrastructure for this effort besides the availability of a micro-pattern facility can be found in section 2.2.2.

2.3.4.2 eRHIC

It has been pointed out in section 2.4, that several MIT faculty and staff members are strongly committed to pursue a new long-term physics program at Brookhaven National Laboratory to establish an electron-proton/ion collider facility (eRHIC) at Brookhaven National Laboratory.

A hermetic inner and outer tracking system will be a crucial component of the central part of a future eRHIC detector. As pointed out in section 2.4.6, the choice of an inner silicon and outer GEM-type tracking detector would be a natural choice considering the requirement for a high-rate tracking device.

It is foreseen to strongly engage in the design and construction of the eRHIC tracking system. It should be stressed that such a facility would provide a continuation in using already existing (MIT LNS silicon laboratory) and proposed (MIT BATES micro-pattern) facilities.

More details on the utilization of the MIT-BATES infrastructure for this effort besides the availability of a micro-pattern facility can be found in section 2.4.6.

2.3.4.3 Linear collider

Over the past three years, the Gas Research and Development task (Task G within the MIT Laboratory of Nuclear Science) has undertaken the study of Gas Electron Multipliers (GEMs) as a new method to coordinate the readout in a Time Projection Chamber (TPC). GEMs offer unique characteristics for TPC readout, which will be necessary for use at a high-energy linear collider. The MIT on campus work is currently supported by DOE funds as part of a generic detector program. In addition some funds for Next-Linear Collider related work have been requested.
This effort would clearly benefit from a micro-pattern facility at MIT-BATES to proceed in the testing of GEM foils besides engineering support.

2.3.5 Layout of a micro-pattern facility at MIT-Bates

The proposed micro-pattern facility based on the foreseen GEM tracking applications by various groups within the Division of Nuclear and Particle Science of the Department of Physics at MIT requires a clean-room setup including various standard equipment to handle GEM foils. Those requirements will be presented in the next section followed by a sketch of the overall layout and equipment including a cost estimate. A list of personnel is provided at the end.

2.3.5.1 Requirements

The proposed micro-pattern facility is expected to carry out as a minimum the following steps in a clean-room setup:

1. Optical inspection of GEM foils using standard microscopic equipment

2. Training, cleaning and preparation of GEM foils

3. Clean packaging of GEM foils

4. Storage of GEM foils

5. Testing GEM foils in standard electrical test setup

    a. LV tests
    b. HV tests
    c. Conditioning
    d. Gas amplification measurements

6. Installation of GEM foils in test setup and final detector chambers

7. Chamber test (Radioactive source test, cosmic ray test, X-ray generator test, laser tests and potentially beam tests at MIT-Bates)

Major required standard laboratory equipment includes:

1. Clean room setup (Class 1000 based the CERN COMPASS experience)
2. Work benches inside clean room
3. Laminar flow system
4. Clean storage cabinet systems
5. Gas supply system
6. Vacuum pump setup
7. Microscope inspection setup
8. Handling and storage setup for radioactive sources
9. Standard electronics equipment such as oscilloscopes and pico Amper-meters
10. High and low-voltage test equipment
11. Standard NIM, CAMAC and VME laboratory units
12. Bar-code reader connected to database system
13. Standard computing equipment

2.3.5.2 Layout and cost

Figure 2.3.6 shows the layout of the clean-room setup (Class 1000) of the proposed micro-pattern facility. The clean-room exhibits one main entrance with the usual entry equipment (Clean-room clothing etc.). The whole facility is divided into three units with a floor space of at least 500 sq. feet each. A subdivision into principle tasks looks as follows:

- Room A: GEM-foil preparation, cleaning and storage
- Room B: Optical inspection and testing
- Room C: GEM foil installation and monitoring

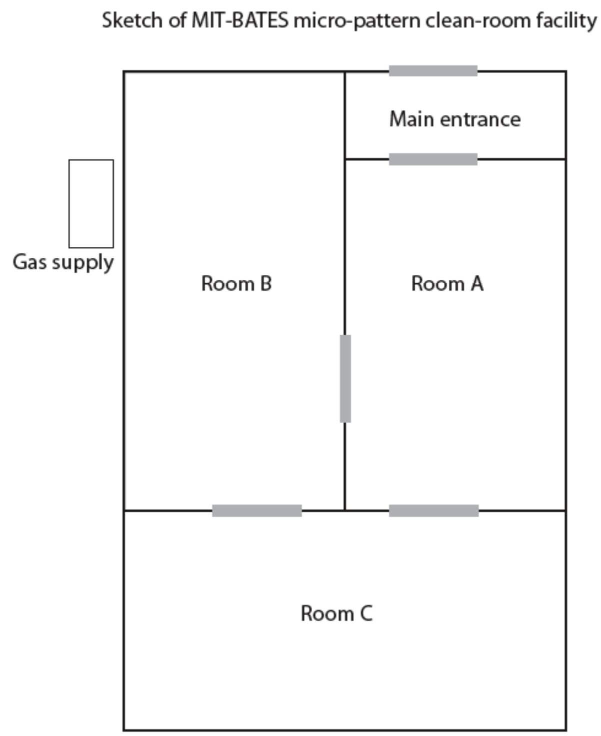


Figure 2.3.6. *Sketch of MIT-Bates micro-pattern clean-room facility.*

2.3.5.3 Equipment and cost

The list below provides an overview of the estimated 'major cost items' for equipment:

- Simple work-benches (3 for each room with ~$1.5k each): ~$13.5k
- Vertical flow laminar hood: ~$8.5k
- Storage cabinets (2 for each room with ~$2.5k each): ~$15k
- Test vessel with pump (incl. windows for laser, source mounts etc.): ~$20k
- Gas system: ~$5k
- Microscope setup: ~$15k
- Standard electronics equipment (3 sets of oscilloscopes and pico Amper-meters with ~$10k+$5k for each room): ~$45k
- Cost for standard NIM, CAMAC and VME laboratory units besides standard computing equipment: ~$100k
- Contingency: ~$25k

The cost for the clean-room setup (Class 1000) as shown in Figure 2.3.28 has been estimated to be $275k. This does not include engineering and setup work, which is expected to be done by local MIT-BATES staff (approx. $60k).

The estimated total cost (clean-room setup and equipment as listed above) amounts to approximately $522k.

2.3.5.4 Manpower

The list below provides an overview of the manpower needs:

- 1 staff physicist (Supervisor of micro-pattern facility)
- 1 research associate

Local engineering and technician support from MIT-BATES during the setup period of the clean-room facility is beneficial and underlines again the advantage for setting up such a new facility at MIT-BATES. Those manpower requirements are included at end of the MIT-BATES proposal in Table 3.1.

2.4 Design of the Electron Ion Collider eRHIC

M. Farkhondeh, W. Franklin, J. van der Laan, R. Milner, C. Tschalaer, F. Wang, D. Wang, T. Zwart

2.4.1 Introduction

Over the last decade there has been substantial international interest in a high luminosity (~1033 nucleons cm-2 s-1) polarized electron-ion collider in the center-of-mass energy range 20 to 100 GeV as the next generation tool for the study of the fundamental quark and gluon structure of matter. Workshops in Seeheim, Germany [2.4.1], at IUCF [2.4.2], at BNL [2.4.3], and at Yale [2.4.4] stimulated the formation of the Electron-Ion Collider (EIC) steering committee at a meeting at MIT in September 2000 [2.4.5] to present the scientific case [2.4.6] at the 2001 Nuclear Physics Long Range Planning Exercise. Presentations and discussions at the Town Meetings at Jefferson Laboratory and at Brookhaven National Laboratory and at the Santa Fe meeting in March 2001 yielded a strong positive endorsement for the scientific case for a high luminosity electron-ion collider. There was a strong endorsement for pursuing the high priority long term R&D necessary for realization of this new facility.

In March 2002, a comprehensive workshop to discuss the collider accelerator design and the scientific case took place at BNL. At this meeting, the leading machine design was identified as a 10 GeV electron ring colliding with the existing RHIC polarized proton and heavy ion beams. This machine configuration is known as eRHIC. At the BNL meeting, it was agreed to develop a conceptual design within three years. The MIT-Bates group agreed to take the lead role in the design of the electron machine.

In March 2003, a subcommittee of NSAC determined that the science of eRHIC was absolutely essential to the future of Nuclear Physics. In November 2003, the twenty year vision for the Office of Science [2.4.7] established eRHIC as a priority for the longer term.

MIT-LNS scientists at Bates have played a leadership role in establishing eRHIC as a major future direction, are playing a vital role in the ongoing eRHIC design and propose to continue this in the coming years. At present, Bates scientists are working with colleagues at BNL, DESY and Budker Institute on the design of the electron linac and the storage ring for the eRHIC collider. This design will be presented in a Zero-Order Design Report (ZDR) document jointly being prepared by BNL and MIT-Bates. It is anticipated that the ZDR will be presented to a review committee in Spring 2004.

The current eRHIC design includes a 5-10 GeV linac and recirculator with polarized electron and positron sources, and a storage ring crossing one of the RHIC interaction regions. In this section, we present a plan for eRHIC design activities at Bates, the manpower required and the capital equipment required for FY06-FY08. There are four major components to the plan, the polarized injector R&D focused on laser development, the linac-recirculator as the injector, and electron storage ring. These are described in sections 2.4.2-2.4.4. An integral part of the eRHIC electron beam is beam polarimetry for which a Bates plan is presented in section 2.4.5. Finally, a summary of manpower and capital equipment for the proposed work is presented in section 2.4.6.

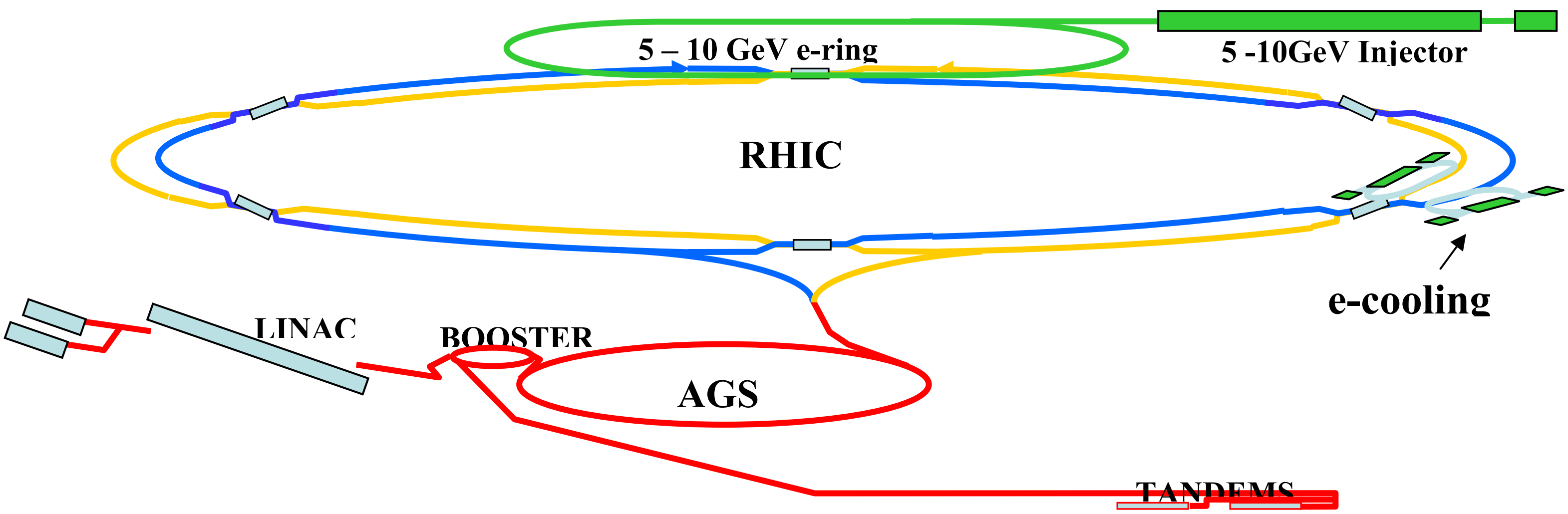


Figure 2.4.1. *Schematic layout of eRHIC accelerator complex.*

The polarized source must address two primary challenges; the time and bunch structure of the ring-ring collider, and the necessary laser power required to achieve the charge per bunch for the stated luminosity for the collider. The polarized source group at Bates has developed innovative injectors over the last two decades, and has developed significant infrastructure including a complete polarized source test stand. This group has the expertise and equipment to efficiently develop the eRHIC source.

While the preferred collider scheme uses an electron ring, there is also interest in developing a high average current linac. This alternative scheme would require development of a high average current polarized photoinjector. This concept will be explored as well and is described in section 2.4.2.4.

MIT-Bates also proposes the development of a Preliminary Design Concept for a 10 GeV electron and positron injector for eRHIC. A major task of the eRHIC effort is to evaluate three possible options for the 10 GeV injector. The options are a normal conducting recirculating linac using well established S-band accelerator technology, a superconducting recirculating linac using cavities similar to those at Jefferson Lab and DESY, and a booster synchrotron designed with special consideration for polarization requirements.

The design plan for the storage ring is centered on computer simulations of lattice design and a detailed study of beam polarization dynamics in the ring. A description of each component of the eRHIC design plan at Bates for FY06-8 is presented here. The presentations also include deliverable objectives in the proposed plan.

2.4.2 Polarized Source R&D for eRHIC

The photoinjector for eRHIC includes the polarized electron source and the beam line elements up to 20 MeV. The polarized source includes a gun chamber with photocathode under UHV conditions, and a laser system capable of producing the required intensity and time structure at the wavelength matching the photocathode excitation energy.

The ability to stack multiple pulses in the storage ring presents a great advantage in achieving high stored average currents from repeated injection with relatively low peak currents in the linac. The stored current of 0.5 A of highly polarized electron beam in a storage ring such as eRHIC normally would represent a modest technical requirement based on present state-of-the-art polarized source technology [2.4.8]. However, the collider nature of eRHIC with synchronized bunches precisely matching the proton bunches represents a great challenge to the injector configuration and the polarized source design. The time and bunch structures for the eRHIC storage ring are shown schematically in Figure 2.4.2. Detailed evaluation of the eRHIC luminosity design value shows that peak currents greater than 20 mA from the source are required. This corresponds to a laser peak power of at least 50 Watts at 800-830 nm. The corresponding charge per bunch is 1.3 pC for bunches ~70 ps long produced at 28 MHz synchronous with the collider ring. This is a challenging technical requirement for a photoinjector.

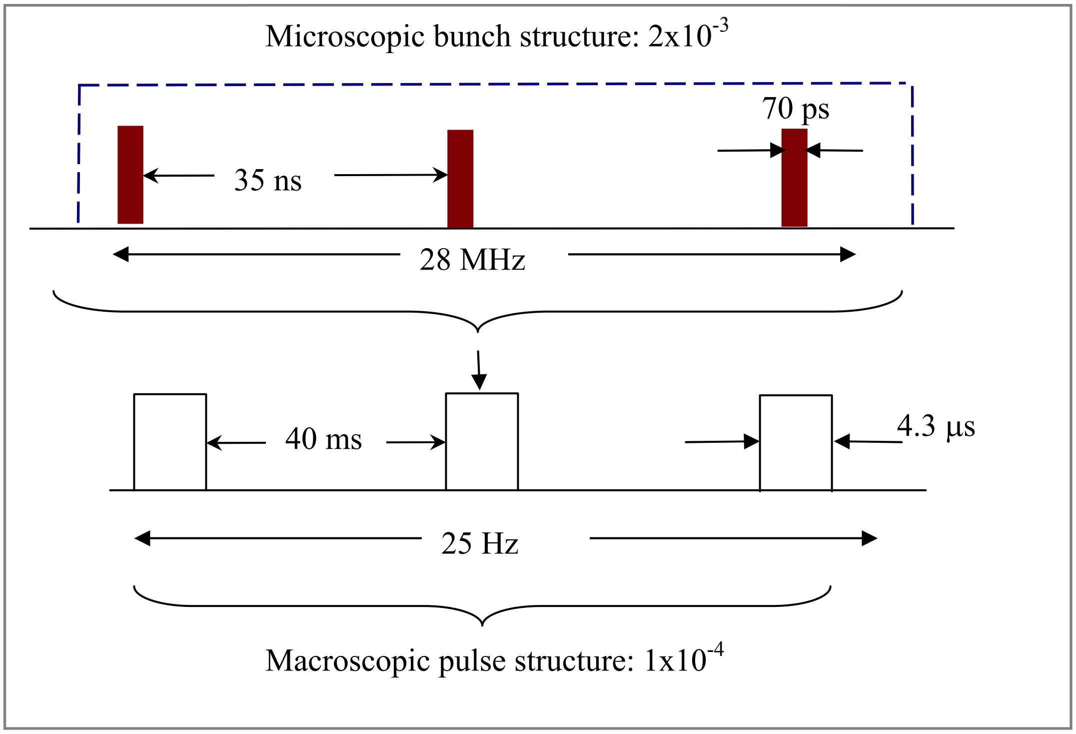


Figure 2.4.2. *Schematic diagrams of microscopic bunch structure (top) and the macroscopic pulse structure (bottom). The duty factors are $2\mathrm{x}10^{-3}$ and $1\mathrm{x}10^{-4}$ respectively. The overall duty cycle of the injector and linac is $2\mathrm{x}10^{-7}$.*

2.4.2.1 Laser development for the eRHIC polarized source

The eRHIC polarized injector is based on photoemission by illuminating high polarization GaAs based photocathodes with circularly polarized laser light at 800-830 nm [2.4.9]. Currently, designs based on two different laser systems are being considered. These two options differ in the time structure of the photoemission drive laser systems and in the electron beam line for bunching and chopping functions. The first option is based on a mode-locked diode laser [2.4.10] capable of producing laser bunches synchronous with the collider. The advantage of this system is that no bunching and chopping of the photoemitted electron beam is required. The mode locked laser is very similar in characteristics to the mode-locked laser used for the G0 experiment in Hall C at Jefferson Lab [2.4.11]. The second option relies on a high-powered DC fiber-coupled diode array laser system similar to one employed for the MIT-Bates polarized source [2.4.12]. In this case, bunching and chopping elements in the linac injector are used to produce bunches synchronized with the collider ring.

For the first option, we propose to develop an R&D program at Bates for the mode locked laser to ensure that the power, bunch length, time stability and the time structure requirements for eRHIC are met. This R&D program is well matched with the capabilities and experience of the Bates polarized injector physicists and engineers with two decades of experience in the field of polarized electron sources [2.4.13]. A schematic diagram of the first option based on a mode locked laser system is shown in Figure 2.4.3.

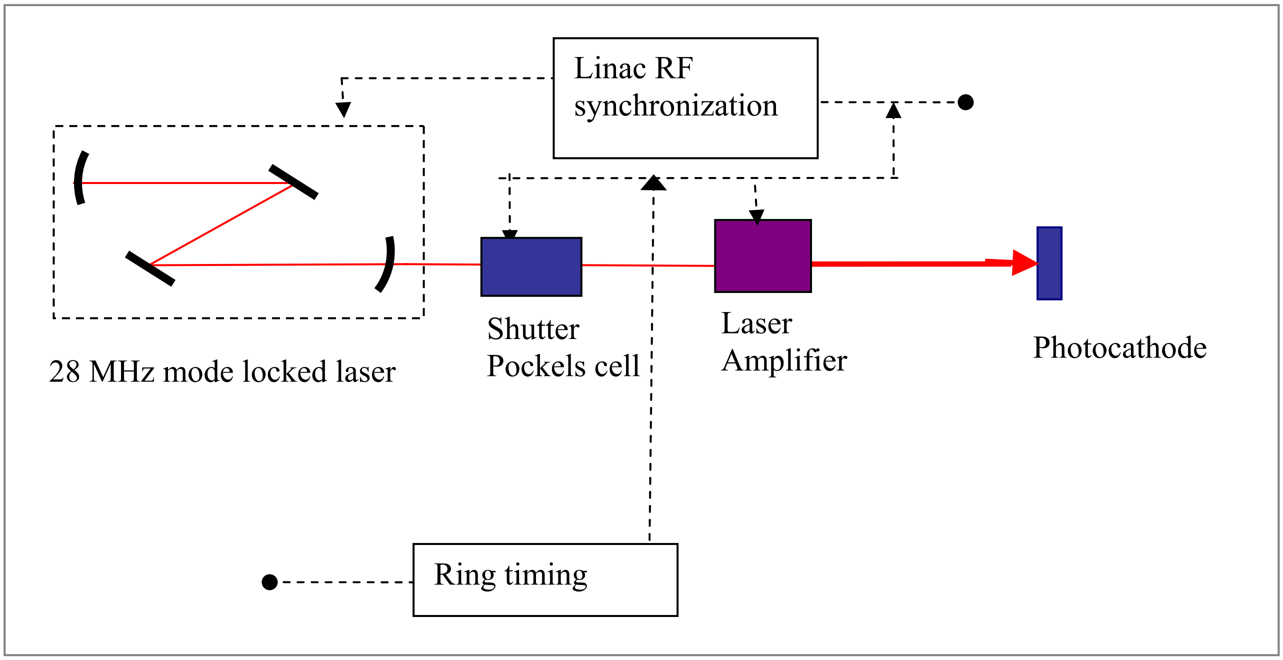


Figure 2.4.3. *Schematic diagram of mode locked laser option for the eRHIC electron injector.*

The second option employs a commercial high power diode laser system. The laser produces DC or pulsed radiation with no microscopic structure. All RF bunch structure and synchronization is introduced to the electron beam by means of RF choppers and bunchers in the linac injector [2.4.14]. Specifically, a high power diode laser system similar to one used in the MIT-Bates polarized injector produces DC radiation ~4.3 μs long directed to the photocathode. The 28 and 2856 MHz RF (or 1300 MHz in case of superconducting linac) structures are introduced into the electron beam by a 102 MHz buncher, a 28 MHz chopper synchronous with the collider ring, a drift space for velocity bunching, and a chopper and buncher system at 2856 MHz (1300 MHz). At the present time, the peak power available from these lasers after circularly polarizing the light are as high as 60 Watts at 810 nm [2.4.12]. This would be adequate for the eRHIC injector provided that the photocathode quantum efficiency (QE) is linear with laser power, i.e. no significant surface charge limit is present.

We propose a modest R&D program for this class of lasers by combining the output of multiple identical diode lasers to achieve higher peak power. The challenge of this option is to ascertain the degree to which the complex bunching and chopping of the electron beam at multiple frequencies is possible. The effort necessary to address this issue is described in the sections below.

2.4.2.2 Beam dynamics simulations for eRHIC source

As stated above, the second option of the proposed polarized injector for eRHIC is based on a DC high power laser system and a complex electron beam bunching and chopping system. This bunching and chopping system should occur after the electrons are accelerated to a few hundred keV but before they are fully relativistic. The 102 MHz buncher and the 28 MHz chopper with a 5-10 m drift in between (Figure 2.4.4) is expected to provide (1) a bunching factor of 5-10 aimed at reducing the peak current requirements from the polarized source and (2) to provide electron bunches that are synchronous with the collider ring. The second set of chopper and buncher at 2856 (or 1300 MHz) is to prepare bunches at the linac frequency for acceleration in the linac. While the laser system for this option is commercially available today with robust and trouble-free operational records, the chopping and bunching system described above is not straightforward and needs further study.

Specifically, the electron beam dynamics between the electron gun and the first few acceleration modules downstream of the chopping and bunching region needs to be studied with advanced computer simulation codes such as PARMELA [2.4.15] and DIMAD [2.4.16]. We propose to carry out these studies in FY06 and FY07 to determine the bunching fraction at 102 MHz, a critical parameter that would shed light on the merit of this option. In addition, beam dynamics parameters including emittance, size, velocity bunching and bunching time stability must be studied in detail.

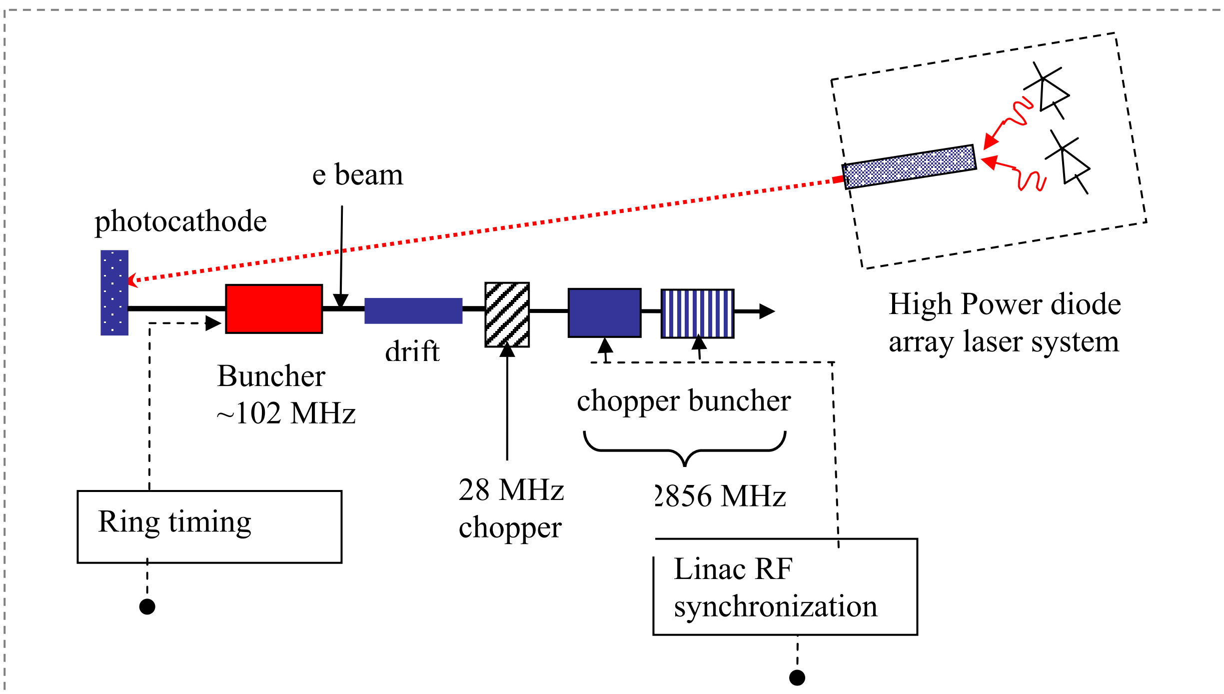


Figure 2.4.4. *Schematic diagram of the laser and the electron beam layout for option two for the eRHIC injector. The DC laser radiation from a high power diode array laser system produces DC photoemission. Bunches of electrons are then produced synchronous with the collider ring by a buncher and chopper system.*

2.4.2.3 Photocathode R&D using the Bates test facility

The polarized injector test facility [2.4.17] at Bates is now used for fully characterizing and certifying polarized guns with high polarization photocathodes prior to installation on the existing main injector. This test setup is a 60 keV beam line that includes a removable gun assembly, Wien filter, Mott polarimeter and Faraday cup. All elements of the beam line are controlled by the EPICS control system. Photocathodes can be fully certified on this setup by measuring QE as a function of laser power to determine surface charge limit effect [2.4.18]. It is also used for beam polarization measurement using the Mott polarization. Further utility of this test setup can include monitoring of photocathode lifetime at low and high gun gap voltage, polarization variation across the surface of the photocathode by illuminating various points of the photocathode with a reduced laser spot.

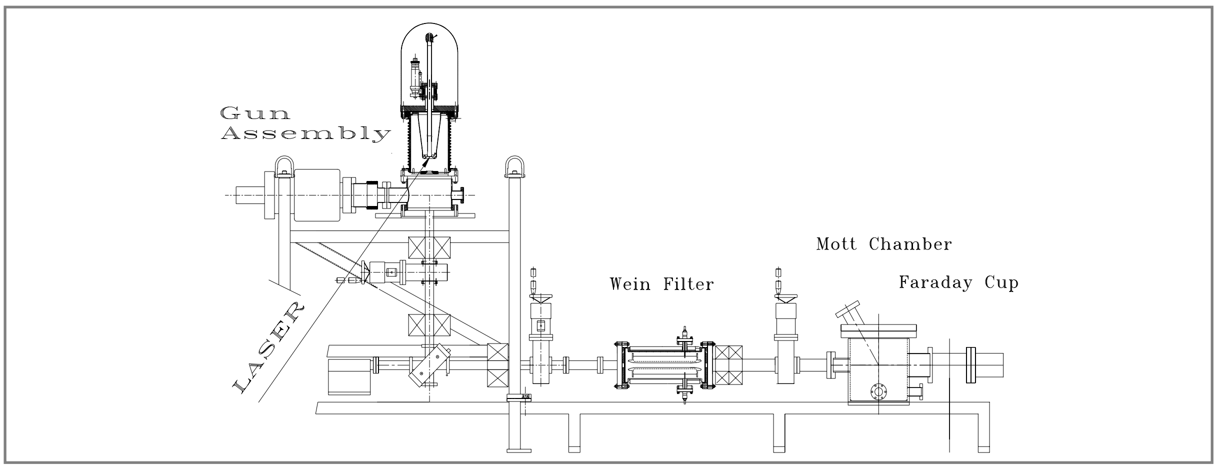


Figure 2.4.5. *Schematic view of the polarized injector test beam facility. The gun assembly includes a gun chamber, an isolation valve and a removable support stand.*

This test facility and the three gun chambers at Bates can also be utilized for R&D on high polarization photocathodes and novel technical issues in polarized gun technology. These issues include: surface charge limit effects on high polarization photocathodes [2.4.19, 2.4.8], and high peak current extractions that are necessary for the eRHIC polarized injector. It can also be utilized for full evaluation and characterization of new high polarization photocathodes with different structures [2.4.20].

2.4.2.4 High average current polarized source for linac-ring collider

In addition to the baseline ring-ring design of eRHIC, a linac-ring design is also under consideration. In this design a high brightness polarized beam generated in a photoinjector is accelerated to 5-10 GeV in a superconducting energy recovery linac (ERL) [2.4.21]. After the collision, the electron bunch is decelerated to an energy of several MeV in the same ERL and damped. The recovered energy is used for accelerating fresh bunches of electron to the interaction point. For the eRHIC design luminosity of 10^{33} $cm^{-2}s^{-1}$, an average current of 400 mA is required from the linac. Therefore, a polarized injector capable of producing these very high average currents is required. This very demanding requirement is well beyond the state of the art. Existing polarized injector designs are capable of producing on the order of 100-200 μA at best [2.4.22]. One method envisioned so far is to direct multiple lasers onto a relatively large photocathode 7-10 cm in diameter [2.4.23]. Clearly, R&D is required to assess the feasibility of this design of a polarized gun. The R&D includes first a complete computer simulation consisting of ray trace of photoemitted electrons and beam emittance and dynamics using PARMELA software package. The second phase of the R&D is to build such a gun chamber and the matching beam line and to acquire mode locked laser systems.

2.4.2.5 Manpower required

The manpower required for injector development including laser development of eRHIC polarized injector, photocathode development on the existing test stand, and beam dynamics simulation will require about 1.5 FTE physicists, one FTE electromechanical technician, and 0.25 FTE mechanical engineer with Photoinjector and UHV expertise. In addition, 0.25 FTE electrical engineer is required to support mode locked laser development and the timing and synchronization issues. Each of these FTE projections is per year for 3 years of effort. Table 2.4.1 summarizes the proposed manpower requirement for the photoinjector plans for FY06-08.

Category	**FTE**		
	FY06	FY07	FY08
Photoinjector physicist	1.5	1.5	1.5
Mechanical engineer	0.25	0.25	0.25
Electrical engineer	0.25	0.25	0.25
Photoinjector technician	1.0	1.0	1.0

Table 2.4.1. *Proposed manpower requirement for the polarized injector activities at Bates for FY06-08.*

2.4.2.6 Capital Equipment required

The first option for the eRHIC polarized injector requires acquisition or development of a mode locked laser at 28 MHz. The laser system can then be used for photoemission tests from high polarization photocathodes on the test stand. The second option for the photoinjector requires acquisition of several commercial high power fiber coupled diode array laser systems to demonstrate the feasibility of combining the output of two or more lasers units and directing the combined radiation onto the gun photocathode. For both of these laser systems, optical elements, power supplies, and Pockels cells are also required.

In addition to the laser equipment, injector R&D requires acquisition of photocathodes from commercial vendors or academic centers, and UHV components and hardware. Table 2.4.2 includes the capital equipment and the hardware required.

Category	**Cost ($K)**		
	FY06	FY07	FY08
Mode locked laser system	100	30	30
High power diode laser	35	15	15
Optical components	25	20	20
HV switches	25	10	10
High polarization Photocathodes	15	5	5
Large area photocathode gun for linac-ring high average current injector	50	100	100
Total	**250**	**180**	**180**

Table 2.4.2. *Capital equipment for polarized injector R&D for eRHIC for FY06-08.*

Summary of Deliverables:

FY2006:

- Specification and acquisition of a ~28 MHz mode locked laser system for option one of eRHIC injector system. Design and acquire synchronization modules.
- Acquisition of a high power diode array laser system for studying high peak current photoemission using multiple diode lasers on photocathode.
- Setup and start electron beam dynamics studies for option two of the injector from the electron gun through the multiple chopper and buncher systems to the first few acceleration cavities. Simulate the bunching gain factor.
- Begin the design of a large area cathode gun intended for producing high average current injector for the linac-ring version of eRHIC.

FY2007:

- Continue testing the 28 MHz mode lock laser and evaluate the feasibility, stability and the power level against the requirement for eRHIC injector.
- Continue photoemission tests for option two injector using multiple high power diode array laser systems and evaluate the electron beam characteristics including emittance, bunch length, peak current and charge limit effects on the photocathode. The Bates test beam facility and the three guns will be used in these tests.
- Evaluate the merit of the two options for the eRHIC polarized injector by considering the results of the simulations and the tests for the two options.

- Selection of one of the above two variants (mode locked laser option or high power diode array laser system with chopping and bunching of the electron beam) for further development.
- Prepare a draft report detailing the design of the polarized injector with the chosen option.
- Complete the construction of the large area photocathode gun and begin photoemission tests. Begin preparation of a draft report on the merit of such a gun for producing high average current for the linac-ring option of eRHIC.
- Photoemission test high polarization photocathodes with different structures. These should include Super lattice structures. Compare the results with the results currently produced by gradient doped GaAsP samples currently in use at Bates and SLAC.

FY2008:

- Preliminary design report of eRHIC polarized injector as part of the eRHIC 10 GeV injector/accelerator for ring-ring option.
- Contingent upon the success of the photoemission tests with the large area photocathode gun, prepare a preliminary design report for a high average current gun for linac-ring option of eRHIC.

2.4.3 eRHIC Injector: Preliminary Design of a 10 GeV Electron/Positron Accelerator

The baseline injector for the proposed eRHIC collider is a 10 GeV machine capable of accelerating either electrons (polarized) or positrons (unpolarized). The successful realization of the eRHIC physics program requires the highest possible luminosity, $\sim 10^{33}$ cm^{-2} s^{-1}, and highest possible polarization of the colliding beams. To maintain the optimum currents, ~0.5 Amps, in the eRHIC electron/positron (e-/e+) ring and preserve the high electron polarization, available from today's photoinjectors, P>70%, the most straightforward technique is to inject into the e-/e+ ring at its operating energy of up to 10 GeV.

Injecting on energy into the eRHIC e-/e+ ring has the three important benefits listed below.

1) **Stability:** Injecting at the full energy allows the e-/e+ ring to run under CW conditions. The stability and control will be superior for a ring with static conditions than one where the beam energy is ramped. This stability will be important for the fine tuning of the e-/e+ ring that will be required to maximize the luminosity of the colliding beams.

2) **Rapid Filling:** Injecting on energy allows for rapid filling of the e-/e+ ring. This will reduce the filling time that is required for the e-/e+ ring. If the filling time is too long it will reduce the integrated luminosity. In practice, the eRHIC collider fill time is likely to be limited by the fill time required for the hadron side. However it is still desirable to keep the e-/e+ fill time short enough so it has a negligible impact on the integrated luminosity. Further, the "on energy" injection allows a so called "top-off" mode of operation where the current in the electron ring is periodically topped-off at intervals which are much more frequent than the hadron storage time. This will increase the maximum achievable luminosity.

3) **No polarization loss:** On energy injection avoids depolarization that is likely to occur if the main ring is ramped. This depolarization occurs principally as spin resonances are crossed during ramping cycle. This effect has been observed at many existing synchrotrons [2.4.24, 2.4.25] and would severely impact the physics program requiring polarization observables.

The performance requirements of an on energy injector are listed below:

- Accelerate polarized electrons to the e-/e+ ring operating energy to a maximum of 10 GeV.
- Preserve the electron polarization during the acceleration process.
- Create and accelerate unpolarized positrons to the e-/e+ ring operating energy to a maximum of 10 GeV

- Fill the e-/+ ring to its operating current of 0.5 A in 10 minutes for either positrons and electrons
- Maintain the capability to “top off” the current in the e-/e+ ring by delivering a pulse of a few mA every few minutes.
- Fill the e-/e+ ring with the bunch structure required by the collider. The present design calls for 30 ns bunch spacing. The ideal injector delivers good bunch to bunch charge uniformity, <1%. The injector should allow flexible filling patterns including other bunch spacings and empty bunches to limit ion trapping and accommodate the e-/e+ ring injector elements’ rise and fall times.

Since the eRHIC program uses stored colliding beams with lifetimes well in excess of one hour the average current requirements of the injector accelerator complex are quite modest. However, details of the collider timing requirements place some additional demands on the injector accelerator complex. Table 2.4.3 lists the necessary properties of the beam delivered to the eRHIC electron/positron ring. Ideally the positron beam would meet the same performance specifications (excepting polarization) as the electron beam.

Beam Energy	10 GeV
Macro Pulse Repetition Rate (during fill)	30 Hz
Electron Bunch Spacing	30 ns
Bunch Train Length	3 us
Charge/Bunch	30 pC
Fill time (Machine on time)	10 minutes
Time between fills (Machine idle time)	>2 Hrs

Table 2.4.3. *eRHIC electron/positron injector accelerator parameters.*

Table 2.4.3 refers to a mode of operation where the eRHIC electron is not “topped-off.” If a “top-off” mode is adopted the accelerator would be required to periodically wake up and deliver a pulse to the eRHIC e-/e+ ring at approximately 10 minute intervals.

While several multi GeV injectors are operational at existing facilities [2.4.26, 2.4.27], there is considerable performance risk for the eRHIC physics program depending on the particulars of the injector design. As a principle design tenet we assert that the maximum luminosity of the collider and maximum polarization of the electron/positron ring should not be limited by the performance of the injector.

Several distinct accelerator topologies appear to have the potential to meet these requirements. The Bates eRHIC team will consider three variants, a recirculating copper S-band linac, a recirculating superconducting linac and a figure-eight booster synchrotron. Considerations that will affect the choice of injector include performance, performance risk, reliability, and cost. Another important factor will be the possible use of the eRHIC injector for multiple purposes on the Brookhaven site. At this point all three topologies are viable options. Each is presented in more detail below.

2.4.3.1 Recirculating Copper Linac

Figure 2.4.6 shows a possible layout of an injector based on a copper linac and recirculator. Here the linac structures are 3 m SLAC 2856 traveling wave sections. The 2856 MHz frequency is well established and the accelerator and high power RF sources are commercially available. The performance characteristics of this technology are known and therefore this design presents little risk for an eRHIC injector.

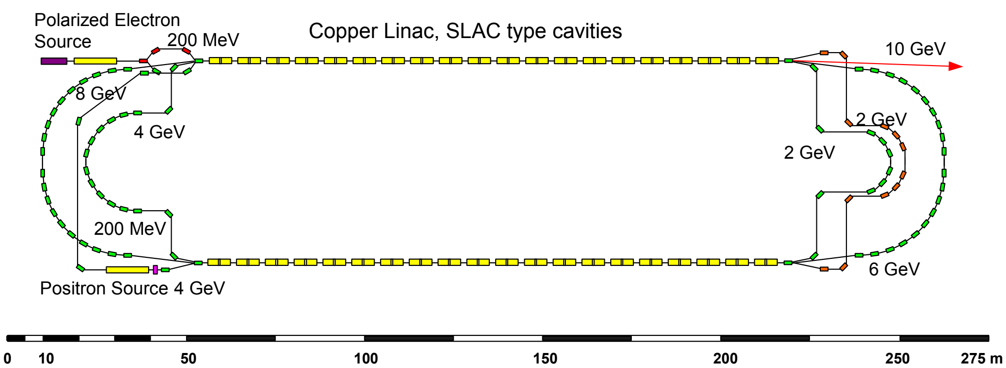


Figure 2.4.6. *eRHIC injector accelerator. A polarized electron beam is accelerated to 200 MeV and injected into a 2 GeV copper linac. At the end of the linac the beam is transported through a 180 deg isochronous recirculation arc into a 2nd 2 GeV linac where the beam is accelerated to 4 GeV. One and a half subsequent recirculations increase the beam energy to a total of 10 GeV. Positron production is also supported.*

The parameters of a copper linac that would satisfy the eRHIC requirements are listed in Table 2.4.4. The Bates staff has considerable expertise in modulator, and S-band klystron and RF technology. The Bates FY06 effort will consider the optimum pre-conceptual design of a copper accelerating "module," where a module consists of a 350 kV power supply, a capacitor bank, a HV modulator switch, a 50 MW klystron, RF waveguide distribution, 2 three meter accelerating sections and their associated RF loads. Low level RF systems, controls and beam diagnostics will also be included.

Linac Frequency	2856 MHz
Linac Gradient	16 MV/m
Number of Linacs	2
Active Linac Length	120 m
Linac Length	170 m
Linac Section Length	3 m
Shunt Impedance	53 MOhm/m
RF Input Power/Section	25 MW
RF Macropulse Length	10 us
Macropulse Current	1 mA
Pulse Repetion Rate	30 Hz

Section Fill time	0.820 us
Klystron Power	50 MW
Klystron Current	300 A
Klystron Voltage	350 kV
Klystrons/Modulator	1
Accelerating Sections/Klystron	2
Number of Sections	80 (40/Linac)
Number of Klystrons	40 (20/Linac)

Table 2.4.4. *RF parameters – Copper S-band eRHIC injector linac.*

The pulse repetition rate of 30 Hz is a modest requirement for a linac of this type. An average power of 30 kW per klystron is expected. These pulses would be line locked for increased stability. The rate is also well matched with the main eRHIC damping time of 7 (58) ms at 10 (5) GeV.

The copper linac would is limited to a smaller number of recirculations (2-3) due to constraints on the pulse widths available from the high power klystrons, i.e. pulses <10 us in duration. The circulation time in the linac is 2 us. So the required RF pulse width for two turns of beam acceleration is 6 us where two microseconds have been allocated for the RF turn on. This is a good match with the pulse widths that are available from these high power 50 MW klystrons. For 6 us of RF, roughly 8 us of video current from the klystron would be required.

The beam pulse length of 2 us is matched to the injector circulation time so that a "head-to-tail" mode of operation may be used. This keeps the current in the linac constant after the initial turn and limits the impact of beam loading.

In principle RF compression (SLED) technology could be used to increase the peak power from the klystron from 50 to ~100 MW (cite SLAC). Higher gradients of 24 MV/m would be possible. However typical pulse widths from these compression schemes are 1-3 us long and therefore not readily compatible with a recirculating linac. Therefore we have not adopted RF compression for this variant.

The staff and infrastructure at Bates is well matched to the prototyping of such a system. This effort could be undertaken at Bates if a decision to proceed with a copper linac design was adopted.

2.4.3.2 Recirculating Superconducting Linac

Figure 2.4.7 shows a possible layout of an injector based on a superconducting accelerator and recirculator. Here the TESLA frequency of 1300 MHz is chosen due to their established performance [2.4.28], but the use of other frequencies between 500 – 1500 MHz is also possible.

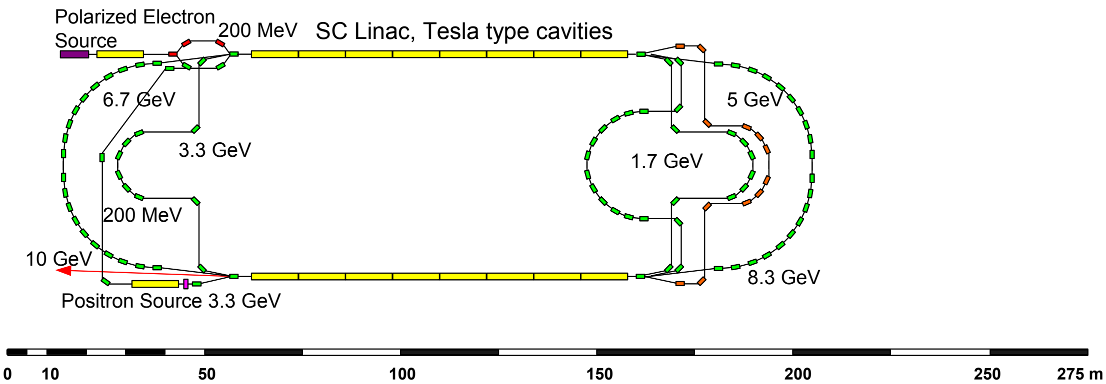


Figure 2.4.7. *Same as figure 2.4.6 except that here the linac is two 1.7 GeV superconducting TESLA style structures. The electron beam is accelerated through 3 revolutions before reaching the maximum eRHIC energy of 10 GeV. Not shown here, a positron damping ring may be necessary to limit beam losses in the superconducting structure. Notice that the scale of the superconducting complex is ~200 m x 50 m while the normal conducting is ~300 m x 50 m.*

The parameters of a possible superconducting linac for eRHIC are listed below in table 2.4.5. As a baseline consideration of the superconducting version we use the parameters of a TESLA type 1.3 GHz accelerator.

Linac Frequency	1300 MHz
Linac Gradient	26 MV/m
Number of Linacs	2
Active Linac Length	64 m
Linac Length	92 m
Linac Cavity Length	1 m
Shunt Impedance (R/Q)	1038 Ohm
Cavities/Cryomodule	8
RF Macropulse Length	40 ms – CW
Macropulse Current	0.5 uA
RF Pulse Repetion Rate	CW - 10 Hz
External Coupling (Q_ext)	2-8e7
Cavity Fill time	1-4 ms
Klystron Power/Cavity	<10 kW
Cavities/Klystron	1
Maximum Heat Load at 2K	5 kW (for CW operation)
Average Heat Load at 2K	400 W (10 minute fill every 2 hrs)

Table 2.4.5. *Parameters for a possible superconducting linac for eRHIC.*

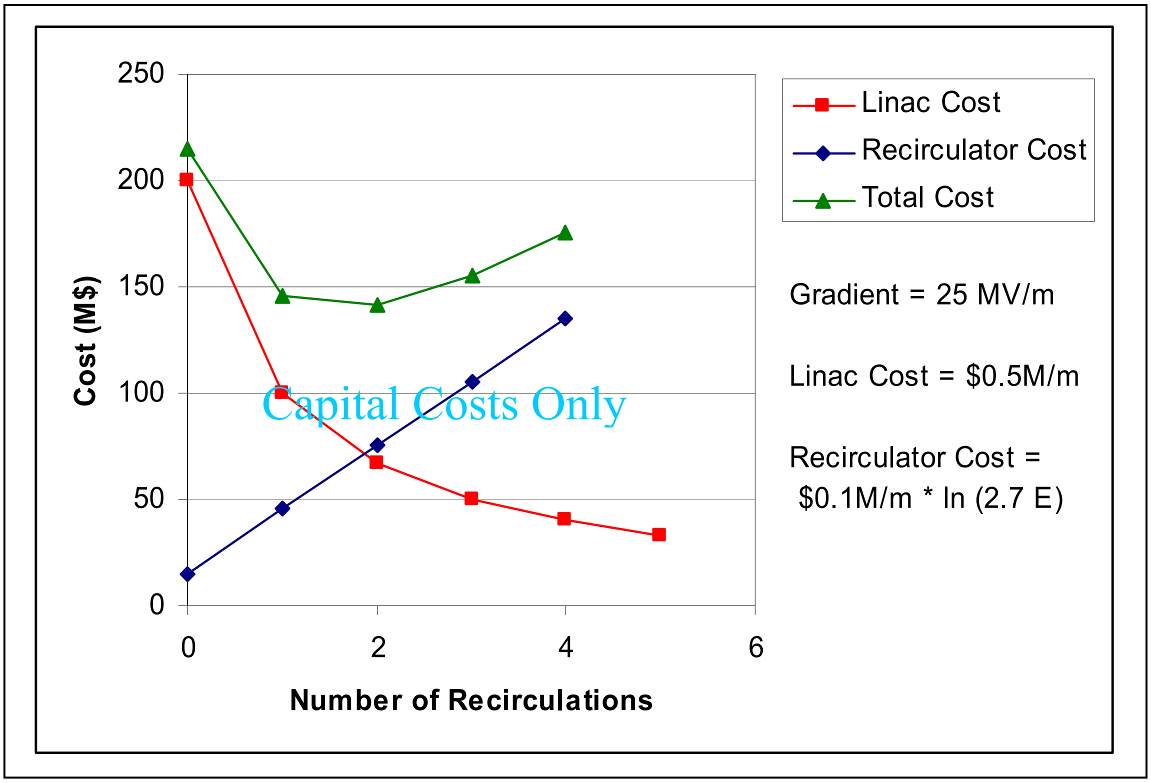


Figure 2.4.8. *Capital cost scaling of a superconducting eRHIC accelerator injector as a function of the number of recirculations. The falling cost for the linac is balanced against a rising cost of the recirculator leading to an optimum near two recirculations (three passes).*

Unlike the copper linac, the number of circulations for the superconducting linac will not be limited by the maximum pulse width but by the complexity of the recirculation. The cost differential for one incremental recirculation scales with the required length of the linac. The incremental linac cost for one additional recirculation is proportional to [1/N – 1/(N+1)] where N is the number of recirculations. Further, each incremental recirculation arc is more expensive than the previous as it is transporting beam at a higher energy and must not interfere with the prior recirculation arcs. Figure 2.4.8 shows capital cost as a function of the number of recirculations, where a very simple cost model is adopted. The superconducting linac is costed at $0.5M per active meter and the recirculator is costed at $0.1M/m multiplied by a weakly increasing function which reflects the additional cost of transporting a higher energy beam. These considerations show that the largest cost benefit is in the first recirculation and that an optimum exists near two recirculations (three passes). Not included are the substantial offset costs of a cryogenic refrigerator, polarized electron source, positron damping ring and other infrastructure. This optimization can be compared with the existing JLAB facility which has four recirculations (5 passes). Here the optimum is at a lower number of turns due to the high gradient, 25 MV/m available from the TESLA accelerating cavities. The Bates FY06-FY08 effort will refine this optimization to assess the optimum superconducting configuration for an eRHIC injector.

The time structure of the beam required to fill eRHIC, (3 μs, 1mA pulses at 30 Hz with a micro structure of 30 pC every 30 ns) gives a very modest requirement on the beam power that the RF sources need to deliver. The average beam current is less than 1 μA and therefore the beam power per cavity is only 20 W. This is to be contrasted with the TESLA collider requirement where the macropulse beam current is 10 mA and the required RF power for the beam is 200 kW per cavity. Clearly a very different RF source is required. For negligible beam power as above and very low wall losses in the superconducting cavity (P~30W at 25 MV/m), the limitations on the minimum required RF power come from control and stability requirements of the superconducting cavities. Several institutions are pursuing active piezo-restrictive tuners that would control the cavity center frequency [2.4.29]. These devices show great promise, but require operation in the cryomass and themselves have resonant behavior which places limits on their performance. Bates has recently developed an RF recycling concept that would make use of an external tuner and phase shifter which would allow the RF sources to be much more closely matched to the intrinsic requirements of ~100 W. This topology could even allow the use of solid state amplifiers rather than klystrons. If successful, this effort would substantially reduce both the capital and the operating cost associated with the eRHIC injector.

Another RF source, a 30 kW, 1.3 GHz the Inductive Output Tube (IOT) is also under development by industry. This is a gridded vacuum tube which does not require the use of a High Voltage modulator. The removal of low level RF from the grid stops the current emission from the cathode, eliminating all AC demand. Further, these devices have very high AC to RF efficiency ~65% due to the bunched nature of the current emission from the cathode. The sinusoidal potential on the RF grid limits the emission angle of the cathode to less than 180 degrees thus increasing the bunching (and RF source) efficiency. Since the IOT is capable of delivering 30 kW it has the ability to overdrive a superconducting cavity system during the long fill time (4 ms) which requires only a few kW in equilibrium. This would makes higher pulse rates possible for a superconducting eRHIC injector accelerator.

The Bates FY06-FY08 effort would include the development of the RF power source, recycling circuit and low level electronics of this device. The RF circuit includes:

- Amplifier. Solid state devices, klystrons and Inductive Output Tubes are all under consideration.
- Standing wave transformer circuit between amplifier and SC cavity. Transmission line or copper cavity geometries are both possible.
- 1 kW low loss phase shifter.
- Controls and low level RF systems.

This device would then be tested at another laboratory with the appropriate superconducting capabilities. Possibilities include JLAB, Stanford, Cornell and BESSY. This activity will require $200K in capital funding.

2.4.3.3 Figure Eight Booster Synchrotron

Another variant of the eRHIC injector that merits consideration is the figure eight synchrotron. This injector topology (Figure 2.4.9) is similar to that proposed for the electron Light Ion Collider (ELIC) presently under consideration by a machine design group at JLAB [2.4.30]. Due to the two opposing 270 degree arcs, this geometry has the attractive feature that the forward spin precession in one half is cancelled by that in the other half, i.e. the net spin precession is zero and independent of energy. Therefore this synchrotron should be able to ramp at moderate rates, ~60 Hz, with little loss of polarization. No spin resonances will be crossed during the ramping process.

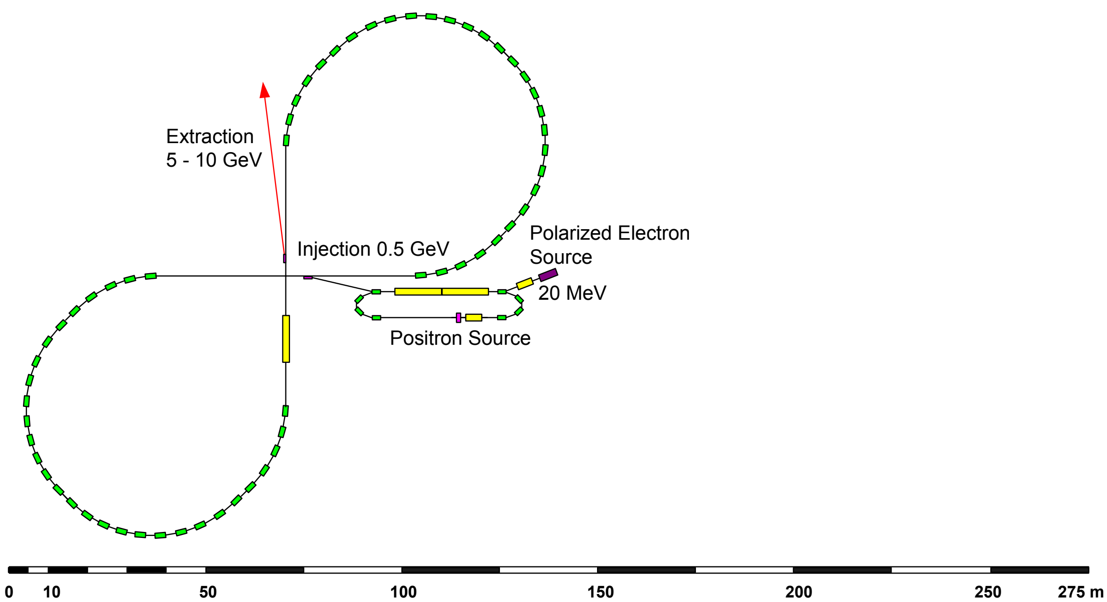


Figure 2.4.10. *eRHIC injector synchrotron with "figure eight" geometry. A 20 MeV injector and 500 MeV linac deliver a 1 mA beam to the synchrotron ring where it is ramped in energy from 0.5 → 10 GeV in ~10 ms.*

The parameters of this type of synchrotron are listed in Table 2.4.7. For this geometry the synchrotron losses per turn at 10 GeV are substantial, 47 MV, so 75 MV of RF voltage must be installed in the ring. However, the average energy during the ramp is only 5 GeV, the supported current is also quite modest, I<10 mA and the synchrotron has a duty factor of less than 50%. Therefore the average beam power is much less than 100 kW. This combination of high voltage and low beam power will probably require superconducting acceleration. These RF parameters are quite different from the main eRHIC electron ring where currents of 0.3 A and synchrotron losses of 10 MV require in excess of 3 MW. The Bates FY06-08 effort will continue to examine this possibility as part of eRHIC injector effort. A critical task for the "figure eight" geometry will be a detailed simulation of the polarization behavior during the ramp to assess the level of polarization that would be achievable for the electron and positron beams delivered to the eRHIC main ring.

Due to the small dipole curvature, 30 m, the ring will have a polarization damping time of 40 s at 10 GeV. This should not cause significant depolarization as the beam circulates in the booster for less than 100 ms.

Maximum Energy	10 GeV
Injection Energy	500 MeV
Circumference	500 m
Dipole Curvature	30 m
Synchrotron Radiation Losses/Turn	50 MV @ 10 GeV
Accelerated Current	1 mA
Peak Beam Power @ 10 GeV	50 kW
Installed RF Voltage	75 MV
Installed RF Power	100 kW
Synchrotron Cycling Frequency	60 Hz
Polarization Damping Time	40 s
Equilibrium Polarization	0

Table 2.4.7. *Parameters for a possible figure eight synchrotron injector for eRHIC.*

2.4.3.4 Positrons

The requirement to deliver 10 GeV positrons to the eRHIC ring adds considerable complexity to the eRHIC injector. As illustrated in Figures 2.4.6 and 2.4.7 our preliminary concept for positron production is accomplished by accelerating electrons through one turn before striking the production target. In the positron acceleration mode the electron transport is indicated in the figures by the red magnets. The subsequent positron transport is then indicated by the green magnets. In the electron mode the red magnets are not used.

The electron energy for positron production will be between 1 and 5 GeV depending on the number of recirculations. A short 200 MeV copper accelerator boosts the positron energy to the same that is delivered by the polarized electron injector. Ideally one captured positron could be achieved per incident electron, maintaining the same currents and eRHIC fill times for both positron and electron beams. The superconducting injector shown in Figure 2.4.7 may require a positron damping ring to limit beam losses in the superconducting structures. A damping ring might also be necessary for the copper linac depending on the acceptance and capture efficiency of the eRHIC e-/e+ ring. The FY06-FY08 eRHIC injector effort will devote 0.5 FTE/year to the design of positron production and acceleration capability.

2.4.3.5 Manpower & Budget Request

The proposed manpower FY06-08 request for the preliminary design of a 10 GeV electron linac/recirculator is shown in Table 2.4.7. At this preliminary stage we estimate that 1.5 accelerator physicist and 1.5 RF engineer is the bare minimum effort required to advance the development of the eRHIC injector. A modest amount of mechanical engineering, 0.5 FTE, is also expected to be required to begin to address the major mechanical subsystems. The single FTE RF technician in FY07 and FY08 is required for the development of the highly efficient RF source.

The accelerator physics and RF engineer effort here is also very complementary with the effort devoted to the eRHIC electron ring. Effort levels below this will have difficulty in sustaining the critical energy necessary to make progress on such a facility. This effort will occur in close collaboration with the RHIC accelerator physics staff at Brookhaven.

Category	**FTE**		
	FY06	FY07	FY08
Accelerator physicist	1.5	1.5	1.5
RF engineer	1.5	1.5	0.5
Mechanical engineer	0.5	0.5	0.5
RF Technician	0.0	1.0	1.0
Total	3.5	4.5	4.5

Table 2.4.7. *Proposed manpower request for designing the electron linac/recirculator eRHIC in FY06-08.*

The necessary items and costs for the development of the highly efficient RF source for a superconducting cavity with small beamloading are listed below in Table 2.4.8.

Item	**Cost ($K)**
1.3 GHz 1 kW Amplifier (Solid State)	10
Amplifier Power Supply	5
1.3 GHz Low Loss ferrite Phase Shifter	30
RF waveguide, directional couplers, attenuators, sources	20
Low level RF systems - control and instrumentation	25
1.3 GHz 30 kW Amplifier (Inductive Output Tube)	100

Total	**190**

Table 2.4.8. *Capital request for development of a highly efficient RF source for a superconducting eRHIC injector accelerator.*

Summary of Deliverables:

FY2006:

- Draft report detailing a self-consistent preliminary design of an eRHIC injector/accelerator based on a recirculating copper linac.
- Draft report detailing a self-consistent preliminary design of an eRHIC injector/accelerator based on a recirculating superconducting linac.
- Draft report detailing a self-consistent preliminary design of an eRHIC injector/accelerator based on a figure-eight synchrotron. Tracking simulation of polarization preservation (or loss) during synchrotron ramping.
- Design of a highly efficient RF source for lightly loaded superconducting cavities suitable for use with a superconducting eRHIC injector.

FY2007:

- Selection of one of the above three variants (copper/superconducting recirculating linac or figure eight synchrotron) for further development.
- Construction and test of RF source for lightly loaded superconducting linacs.

FY2008:

- Preliminary design report of eRHIC 10 GeV injector accelerator.

2.4.4 The Electron Storage Ring for eRHIC

The eRHIC electron ring is designed to have a circumference of one third of the RHIC circumference and it will be installed in a separated tunnel from RHIC. The electron-ion interaction will take place at RHIC IP12 location.

2.4.4.1 Design Overview

To meet the wide scope of the eRHIC physics experiments, the electron ring is required to have a large energy range of 5-10 GeV. And in order to achieve high luminosities in all collision scenarios, the electron beam emittance need to be adjusted over one order of magnitude to match the beam parameters of various hadron species of variable energies. Another distinguish design feature is that the electron (or positron) beam must be highly polarized longitudinally at the interaction point. These design requirements are very different from the comparable electron ring designs of e^+e^- colliders, PEP II [2.4.31] and

KEKB [2.4.32], and somewhat different from the electron (positron) ring of the only existing lepton-hadron collider HERA [2.4.33] as well.

The primary performance goals for eRHIC collider are outlined here. [2.4.34]

- To achieve peak collision luminosities of 10^{32} to 10^{33} $cm^{-2}s^{-1}$ between 10GeV electrons and 250 GeV protons.
- To provide a wide tuning range for beam energy (5-10 GeV) and for beam emittance adjustment to accommodate collisions with various ion species of variable energies for high luminosities.
- To provide a high degree of longitudinal beam polarization (> 70%) at IP.
- To store high current (0.45A) and high single bunch charge (120 bunches, $1*10^{11}$ electrons per bunch) with adequate lifetime.
- To provide polarized positron beam at 10 GeV.
- To produce acceptable detector background conditions.

The key features of the ring design are: [2.4.35] [2.4.36] [2.4.37]

- Flat beam, head on collisions.
- Low β_y* values at the interaction point (IP).
- High emittance ratio of the elliptical electron beam at the IP.
- Antisymmetric solenoidal spin rotators in the IR straight with pure longitudinal spin at 8.5 GeV. 4% reduction at 10 GeV and 20% reduction at 5GeV.
- Flexible FODO arc structure for electron beam emittance adjustment.
- Wigglers to increase synchrotron radiation damping for higher beam-beam tune shift limits at low energy.
- Electron path length adjustments up to 0.9m.
- Adequate vertical closed orbit correction capacities for high beam equilibrium polarization.
- Full energy polarized electron beam injector with bunch filling and top-off capacities.
- Reliable high power RF system.
- Low field solenoids around the ring to suppress electron-cloud effect for positron beam.
- Low-photodesorption, low impedance, high radiation power resistant vacuum chamber.
- Provisions for longitudinal polarimeter operation in the IR straight.

The nominal parameters of the main electron ring and the e-p collision are listed in table 2.4.8.

Parameter	**Unit**	**Electron**	**Proton**
Energy E	[GeV]	10	250
Circumference	[m]	1277.948	3833.845
Arc Dipole radius	[m]	81.02	
Beam emittance radio k=εy/εx		0.18	1
Beam emittance εx	[nm.rad]	53	9.4

Beta functions at IP βx / βy	[m]	0.19/0.27	1.08/0.27
Beam-beam tune shift		0.08	0.0065
RF frequency	[MHz]	~478.6	~197.4
RF Voltage	[MV]	25	
Bunch Length	[cm]	2.1	25
Number of Bunches		120	360
Bunch Separation	[ns]	35.52	35.52
Synchrotron Radiation Loss/turn	[MV]	11.74	N/A
Synchrotron Damping Time τx	[ms]	7.4	N/A
Particles per Bunch		$1.0x10^{11}$	$1.0x10^{11}$
Total Current	[A]	0.45	0.45
Linear Radiation Power Density, Arc	[KW/m]	9.69	N/A
Luminosity £	[$cm^{-2}s^{-1}$]	$4.4x10^{32}$	

Table 2.4.8. *Parameters of the main electron ring and the e-p collision for eRHIC.*

The parameters listed are nominal parameters for the 10 GeV electron and 250 GeV proton collisions. A higher luminosity value, which is calculated from a set of optimized parameters, is $1x10^{33}$ $cm^{-2}s^{-1}$.

2.4.4.2 Proposed design work for the electron storage ring for eRHIC

The work proposed here for the electron storage ring for eRHIC consists primarily of producing a detailed design of the ring and simulation of various effects.

Machine Design and simulation studies
The following are descriptions of essential design works of machine optics, beam physics and key technical issues.

- **Machine Optics**
  IP region optics design optimization (bind with RHIC), ring lattice completion and optimization, technical system (physics requirement) specifications.
- **Dynamic Aperture**
  Chromaticity correction schemes for large 3d dynamic apertures, including local chromaticity corrections at IR region. Tracking with radiation and errors.
  Two sympletic tracking codes LEGO [2.4.38] and SAD [2.4.39] developed at PEP II and KEKB could be serve many of the tracking needs. Efforts of implementation and modification (joint effort) for special needs are required.
- **Beam-Beam Tracking**

Beam-beam effect tracking in eRHIC design has special issues that are different from the existing colliders, like lepton-hadron strong-strong collision (There are studies for quasi strong-strong collision in e^+e^- colliders [2.4.40]), coherent beam-beam with unequal-circumference collider [2.4.41] etc... New tracking code development efforts are inevitable.

- **Beam Polarization Simulations**
  The beam polarization simulations provide the information of beam equilibrium polarization in considerations of synchrotron radiation, machine errors, nonlinearity, particle distributions, and pre-polarized beam during injection. Beam-beam effect on polarization is also a subject must be addressed. Efforts for tracking code improvement (SLICK [2.4.42], SLICK3D [2.4.43]) or development are needed for better polarization evaluation.
- **Beam Instability Study**
  Dominate issues are beam intensity (average and single bunch), life time etc…
  This includes a wide range of physics issues. Many of them closed related to machine technical system design details like impedance of vacuum chambers, RF, feedback etc... Works include simulations and system specifications.
- **RF system**
  A reliable high power RF system. Choice of frequency, technology (Copper of Super conducting), HOM suppress, high power and low power RF etc...

A significant effort on the RF is to evaluate both room temperature copper and superconducting systems for the electron ring. And for the ring RF system, the goal is to achieve an optimized RF system design which provides the proper tuning range to synchronize the electron beam with the proton beam at the different proton energies.
Two cumulative effects are to be considered early in the design of the HOM couplers. These are the multi-bunch instabilities caused by resonant higher-order modes in the cavities, excited by the beam, and single-passage effects due to the wake fields excited by the beam during its transit of a cavity (e.g. head-tail turbulence, bunch lengthening, and synchro-betatron resonances). To accommodate the high average power dissipation and wide range of beam-loading conditions associated with the storage mode operation, cavity tuning and coupling system with considerable adjustability is required.

Experimental Tests

The establishment of a Center for Accelerator Science at Bates would allow the South Hall Ring to serve as a laboratory for a set of beam studies related to eRHIC. Funding for such studies is not requested in this document, but it is clear that a limited set of experiments could complement the simulation work in a very useful manner. For example, a test could be carried out in the east straight section of the South Hall Ring to study the degree of equilibrium polarization for elliptical and flat beams (high and low emittance ratios respectively).

To achieve luminosity at eRHIC as high as $10^{33}cm^{-2}s^{-1}$ for 10/250 GeV, e-p collision, the electron beam emittance ratio is a critical parameter [2.4.44]. The need to preserve high equilibrium polarization imposes a major constraint [2.4.45] on the realization of higher emittance ratio for electron beam. A high polarization, high emittance ratio elliptical electron beam test would address the critical issue of whether a flat beam (low emittance ratio of 5%) could be effectively transformed to an elliptical beam (higher emittance ratio of 20%) in the IP region where spin direction is nearly longitudinal. There are theoretical predictions [2.4.46] and proof-of-principle experiments [2.4.47] for such a beam emittance adapter, but there has been no experimental demonstration in a storage ring yet. Such an experiment would also test whether a high emittance ratio beam in a storage ring with high equilibrium polarization is possible if the emittance adapter proves practically difficult.

2.4.4.3 Manpower required

The manpower requirements for the proposed design studies for eRHIC are summarized in table 2.4.9. The 4 FTE of accelerator physicist and the 1.5 FTE of RF engineer listed in the table is to produce a preliminary conceptual design report for the eRHIC electron ring. This table does not include manpower or capital equipment funding for an experimental program in the South Hall Ring.

Category	**FTE**		
Ring design for eRHIC	**FY06**	**FY07**	**FY08**
Accelerator physicist	4	4	4
RF engineer	1.5	1.5	1.5
Total	5.5	5.5	5.5

Table 2.4.9. *Manpower required for designing the electron ring for eRHIC for FY06-08.*

Deliverables:

2006:

- Draft of preliminary design report. First round machine optimization for high luminosity from beam dynamics and polarization simulations.
- Organize and coordinate long term tracking code development efforts. Targeting specific machine physics issues for eRHIC and applicable to future beam-based diagnostic and controls.
- Identify key technical challenges e.g. high radiation resist vacuum chamber etc…

2007:

- Continue ring design with technical system specifications.
- Join effort to resolve technical issues to merge the e-ring to RHIC complex.

2008:

- A complete pre conceptual design report for the eRHIC electron ring.
- Comprehensive collider ring physics simulations tools development progress.

2.4.5 Electron Polarimetry for eRHIC

Accurate polarimetry in the electron storage ring will be essential for the eRHIC project. Polarimeters must provide accurate measurements as a function of time without destroying the stored beam. A panel at the Workshop for Electron Beam Polarimetry for EIC at BNL [2.4.47] concluded that the technique of laser backscattering will provide a tractable method for measuring both transverse and longitudinal components of the beam polarization for eRHIC. Nevertheless, considerable effort will be required to reach the desired 1% level of statistical and systematic accuracy. To make this possible, the polarimeter must be designed in parallel with the storage ring.

2.4.5.1 Compton Polarimetry at Bates

Physicists at MIT-Bates have substantial experience in the area of electron polarimetry for storage rings. The MIT-Bates Compton Polarimeter [2.4.48] acts as a continuous monitor of the stored electron polarization in the South Hall Ring (SHR) for experiments with BLAST. It contains several components which will be required in a laser backscattering polarimeter for eRHIC, including a high-powered laser system, optics for laser transport and helicity control, an interaction region for interception of the electron beam, and a gamma ray calorimeter for the detection of highly energetic scattered photons. The polarization is extracted from an asymmetry in the scattering of circularly polarized laser light from the stored electron beam. The asymmetry can be modeled accurately and rises with electron energy, making Compton polarimetry well suited for high energy storage rings. The Bates polarimeter is the first to operate continuously in a storage ring below 1 GeV with currents comparable to those to be used in eRHIC. Fig. 2.4.11 shows measurements of the asymmetry for a representative sample of data taken at 850 MeV. Bates has developed precise measurement techniques with this polarimeter for beam currents ranging from as little as 1 mA to more than 200 mA. The polarimeter has been used to optimize injection of polarized beams into the ring for BLAST experiments, study sensitivity of the stored beam polarization to SHR tune, and to demonstrate adiabatic reversal of the polarization of a stored electron beam with high efficiency.

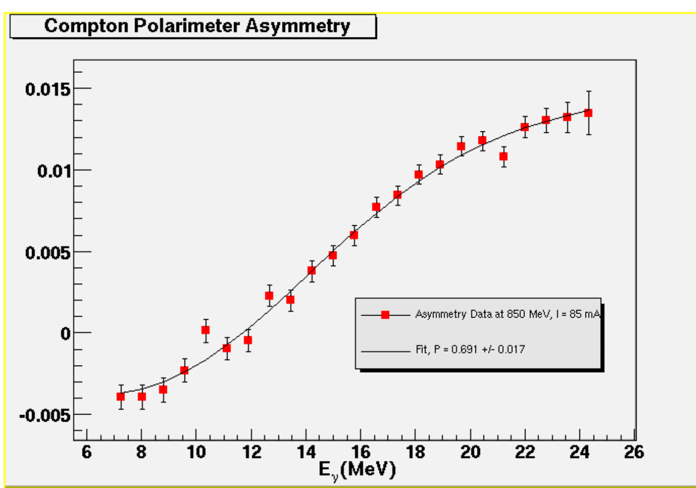


Figure 2.4.11. *Asymmetry data as a function of scattered gamma ray energy from the MIT-Bates Compton Polarimeter . The data were taken at 850 MeV over a sixty minute interval. The curve represents a fit to data which is used to extract the beam polarization (.691+/- .017).*

The MIT-Bates Compton Polarimeter could provide valuable information for a limited set of beam studies relevant to eRHIC in the South Hall Ring within the context of a Center for Accelerator Science. No funding for such studies is requested in this document, but the preservation of an operational polarimeter for the South Hall Ring is a prerequisite for such experiments. The polarimeter is presently configured to measure the longitudinal component of the beam polarization as needed for BLAST experiments. For operation with transverse polarization and without a Siberian Snake in the South Hall Ring, some additional development would be necessary.

2.4.5.2 Research and Development for eRHIC Polarimetry

Bates physicists have participated in preliminary discussions of eRHIC polarimetry. Two Compton polarimeters have been proposed for the eRHIC electron ring. One polarimeter will directly measure the longitudinal component of the beam polarization near the collider's interaction point using techniques similar to those of the Bates polarimeter. A second polarimeter will be located in a section of the ring in which the beam polarization is transverse. The placement and requirements of these devices will be closely coupled to the properties of the electron beam. A number of considerations related to the polarimeter could influence the final ring design.

Each of the eRHIC polarimeters will require an advanced laser system. The design of the laser system must balance considerations such as power, stability, figure of merit, and pulse structure. To maximize the polarimeter's analyzing power, use of an ultraviolet laser is being strongly considered, which will require careful treatment of the transport optics. Laser power could be enhanced through use of an amplification cavity, which will require special considerations for the design of the interaction region with the electron beam. Electron polarization can vary from bunch to bunch in storage rings [2.4.49], and the laser system should be designed such that the polarization of each electron bunch can be accurately extracted.

Each polarimeter at eRHIC will require a full-fledged detector system for scattered photons, scattered electrons, or both. While Compton polarimeters [2.4.50, 2.4.51] have usually relied on the detection of scattered photons, the exceptionally intense beams of eRHIC pose challenges for the design of a photon calorimeter. Advantages may be gained through the use of a magnetic spectrometer or channel for scattered electrons. Such devices are in use at tagged photon facilities [2.4.52], but will face other challenges in analyzing scattered electrons with energies of nearly 10 GeV without disruption of the stored beam.

Accurate modeling of the interaction between the laser and electron beam will be crucial in answering many of the open questions related to polarimeter design, an area in which close interaction between the ring design and polarimetry groups is important. Bates personnel have substantial laser expertise and the lab possesses hardware and instrumentation which could be used in the development of a prototype laser system. In addition, Bates physicists can contribute substantially to the development of a detector system.

2.4.5.3 Budget Request

Support is requested for design work for eRHIC polarimetry to be carried out by Bates physicists during the period from 2006-2008. Duties will include development of an appropriate laser system, modeling the interaction of lasers and electron beams, and detector design. No new capital equipment is requested for this purpose, but it is anticipated that some of the lab's existing laser infrastructure can be employed for prototype design and testing.

Project	**Manpower**	**FY06 FTE**	**FY07 FTE**	**FY08 FTE**
ERHIC polarimetry	Physicist	0.5	0.5	0.5
Total		0.5	0.5	0.5

Table 2.4.12. *Manpower request for FY06-08 period.*

Deliverables:

2006:

- Development of simulation for eRHIC polarimeter
- Report on initial eRHIC simulation results including recommendation for the type of detector to pursue.

2007:

- Preliminary design of detector system for eRHIC polarimetry.
- Preliminary design of laser system for eRHIC polarimetry.

2008:

- Detailed design of detector and laser system for eRHIC polarimeter consistent with parameters of eRHIC ring.
- Preparation of design report for eRHIC polarimetry

Summary of manpower requirements

In summary, the eRHIC electron machine design plan at Bates for FY06-8 has three components: the polarized injector, the linac-recirculator, and the storage ring. The manpower requirement for the proposed work was presented for each are in sections 3-5. Here the combined total manpower is presented in table 2.4.14.

Category	**Total FTE**		
eRHIC	**FY06**	**FY07**	**FY08**
Photoinjector physicist	1.5	1.5	1.5
Accelerator physicist	6.0	6.0	5.5
Polarimeter physicist	0.5	0.5	0.5
RF engineer	3.0	3.0	3.0
Mechanical engineer	1.75	1.5	1.0
Electrical engineer	0.50	0.25	0.25
Photoinjector Technician	1.0	1.0	1.0
Grand Total	**14.25**	**13.75**	**12.75**

Table 2.4.14. *Summary table for manpower required for the eRHIC electron machine design activities at Bates for FY06-08.*

The summary of capital equipment for eRHIC electron machine studies at Bates for FY06-8 is presented in table 2.4.15.

Category	**Cost ($K)**		
	FY06	FY07	FY08
Polarized Injector with ring-ring option	200	80	80
Polarized source for linac-ring option	50	100	100
Linac-recirculator	100	50	50
Total	**350**	**230**	**230**

Table 2.4.15. *Summary table for capital equipment required for the eRHIC electron machine design activities at Bates for FY06-08.*

2.4.6 eRHIC tracking detector design, R&D and construction facility

D. Hasell, R. Milner, B. Surrow

2.4.6.1 Introduction

An electron-proton/ion collider facility (eRHIC) is under consideration at Brookhaven National Laboratory. MIT-BATES laboratory is already strongly engaged with the design of an electron linac and a storage ring for the eRHIC collider facility. This high energy, high intensity polarized electron/positron beam facility to collide with the existing RHIC heavy ion and polarized proton beam would significantly enhance the exploration of fundamental aspects of Quantum chromo-dynamics (QCD), the underlying quantum field theory of strong interactions [2.4.53]. Several faculty and staff members within the Laboratory for Nuclear Science at MIT are strongly committed to pursue this long-term physics program at Brookhaven National Laboratory.

Such a new facility will require the design and construction of a new optimized detector. The previous experience of several MIT faculty and staff members in the detector requirements at the unpolarized ep collider HERA will significantly aid this endeavor. The detailed design is closely coupled to the design of the interaction region and thus to the machine development work in general. The foreseen involvement of MIT-BATES in both accelerator and detector design will provide a stimulating environment to come up with an optimized detector design.

The target luminosity at eRHIC of 10GeV electron/positron beam on a 250GeV proton beam amounts to approximately $1 \cdot 10^{33}$ $cm^{-2}s^{-1}$ at a bunch-crossing time of 35ns. This sets stringent requirements on the high-rate capability of the specific detector type including the readout and trigger system.

The current involvement at the RHIC SPIN physics program within the STAR experiment focuses in its upgrade program on the design of a new inner/forward tracking system based on a combination of silicon and GEM-type tracking detectors. A dedicated micro-pattern detector facility is part of this proposal and is foreseen to be a center piece of future detector work by several experimental particle and nuclear physics groups at MIT.

Silicon and GEM-type tracking detectors are intrinsic fast detector systems which are being utilized in several current high-rate experiments world-wide.

The demand for high-rate tracking, intrinsically fast and precise tracking detectors by a future dedicated eRHIC detector would make silicon and GEM-type tracking detectors a natural choice. It is foreseen to consider those detector technologies in the design of the tracking system of a future eRHIC detector and strongly engage with several MIT faculty and staff members in this effort. This would therefore make use of the existing (LNS silicon laboratory) and proposed (Micro-pattern detector facility) detector facilities at MIT.

The next section provides a brief overview of the eRHIC detector design followed by an outline of a future eRHIC tracking detector R&D and construction facility. It should be stressed that such a facility would also provide a continuation of infra-structure which is already foreseen for the STAR tracking upgrade at MIT-BATES besides the LNS silicon laboratory.

2.4.6.2 Outline of the eRHIC detector design

The following discussion will be restricted to the nominal eRHIC collider mode operation of a 10 GeV electron/positron beam colliding with a 250 GeV proton beam. Simple four vector kinematics in ep collisions which involves an electron and a proton in the initial state and a scattered electron along with a hadronic final state in the final state can be used to study analytically the energy and angular acceptance of the scattered electron and hadronic final state as a function of the main kinematic quantities in deep-inelastic scattering (DIS), x and Q^2 [2.4.54]. This provides a first understanding of the final state topology. Q^2 is the negative square of the momentum transfer between the incoming and scattered electron. The Bjorken scaling variable x is interpreted in the Quark-Parton model as the fraction of the proton momentum carried by the struck quark.
The hadronic final state consists of the current jet which emerges from the struck quark characterized by its polar angle and energy.

Figure 2.4.12 shows isolines of constant electron energy (a) and constant scattering angles (b) as well as lines of constant y values (1, 0.1, 0.01). The kinematic variable y is given in terms of x and Q^2 ($y = Q^2 / sx$) and refers to the inelasticity in the rest frame of the proton. The kinematic limit is given by y=1. The scattering angle is measured with respect to incoming proton beam which defines the positive z axis. Electron tagging acceptance down to at least 177º will be necessary to provide acceptance in Q^2 below $1GeV^2$. The energy of the scattered electron is less than 10GeV and is in particularly small in the region of low x and medium to low values in Q^2. This sets stringent requirements on trigger and reconstruction efficiencies.

Figure 2.4.12 shows isolines of constant current jet energy (c) and angle (d). The energy of the current jet is rather small in the low x and medium to low Q^2 region and overlaps to some extend with the scattered electron. The current jet energy increases towards the forward direction in the region of high x and Q^2 values. This will require e/h separation capabilities in particular in the rear direction (incoming electron direction) and increasing jet energy measurement capabilities in the forward direction (incoming proton direction).

The following minimal requirements on a future eRHIC detector can be made:

- Measure precisely the energy and angle of the scattered electron (Kinematics of DIS reaction)

- Measure hadronic final state (Kinematics, jet studies, flavor tagging, fragmentation studies, particle ID)
- Missing E_T measurement for events involving neutrinos in the final state (Electroweak physics)

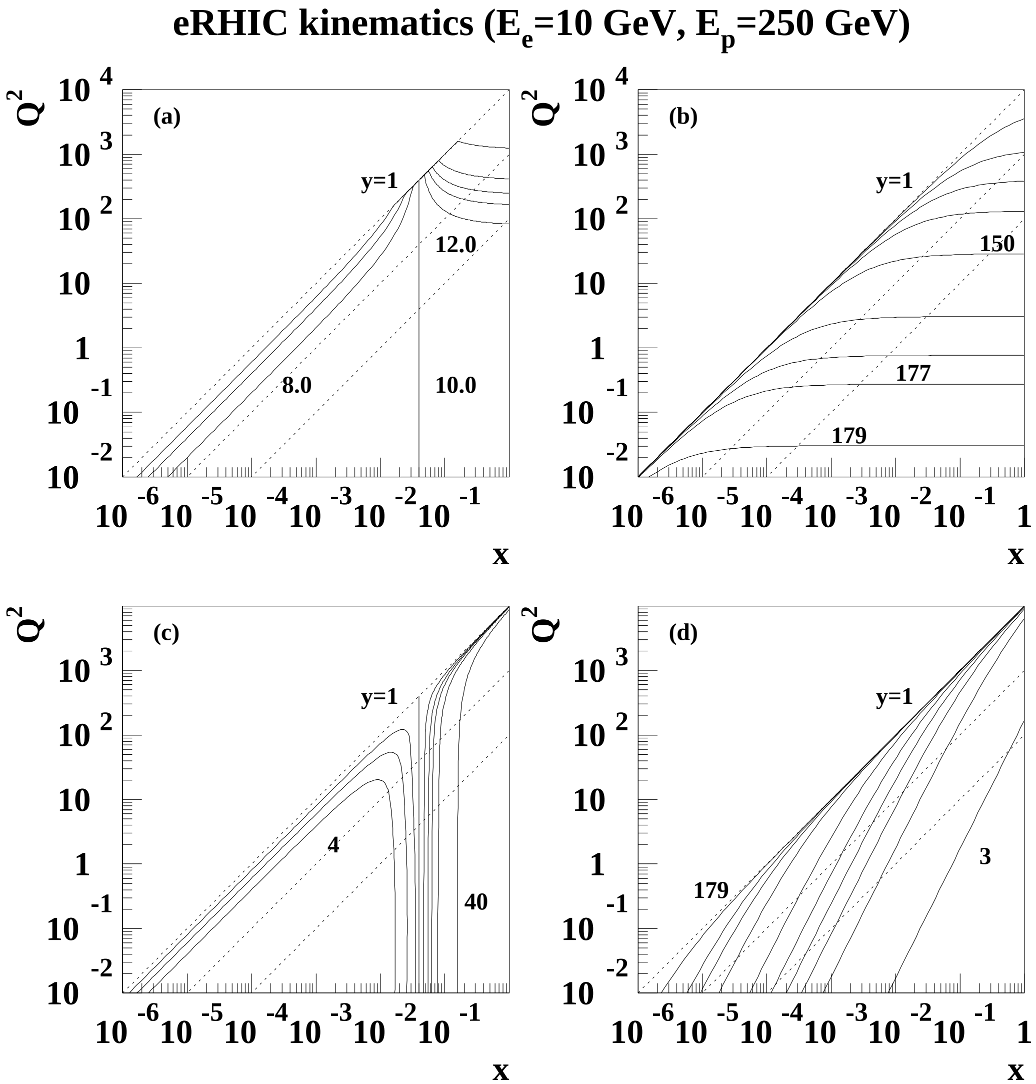


Figure 2.4.12. *The dashed lines represent lines of constant y values (1, 0.1, 0.01). The electron beam energy amounts to 10GeV whereas the proton beam energy is 250GeV. Isolines of constant electron energies (4, 6, 8, 10, 12, 14, 16, 20 and 40GeV) (a), electron scattering angles (30º - 150º in steps of 30º and 170º, 175º, 177º and 179º) (b), current jet energies (4, 6, 8, 10, 12, 14, 16, 20 and 40GeV) (c) and current jet angles (3º, 30º - 150º in steps of 30º and 170º, 175º, 177º and 179º) (d).*

In addition to those demands on a central detector, the following forward and rear detector systems are crucial:

- Zero-degree photon detector to control radiative corrections, measure Bremsstrahlung photons for luminosity measurements and in e-A physics to tag nuclear de-excitation
- Tag electrons under small angles (Study of the non-perturbative/perturbative QCD transition region and luminosity measurement from Bremsstrahlung ep events)
- Tagging of forward particles (Diffraction and nuclear fragments)

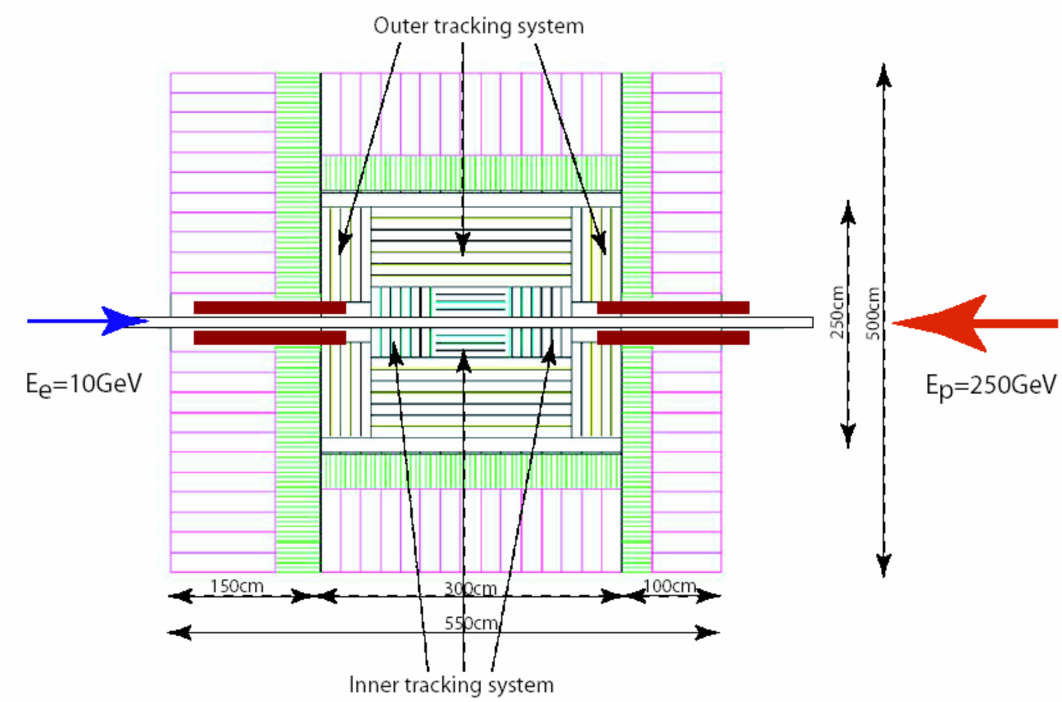


Figure 2.4.13. *Conceptual GEANT detector implementation of the main central eRHIC detector components. The inner and outer hermetic tracking system is surrounded by an axial magnetic field on the order of 1-2T. The tracking volume is surrounded by a hermetic calorimeter system in the rear, barrel and forward direction.*

Figure 2.4.13 show the first conceptual GEANT detector implementation of the above requirements on a central detector. The hermetic inner and outer tracking system is surrounded by an axial magnetic field on the order of 1-2T. The tracking volume is surrounded by a hermetic calorimeter system in the rear, barrel and forward direction. The calorimeter system is subdivided into electromagnetic and hadronic sections which are then in-turn subdivided into certain size towers. The inner most double functioning dipole and quadrupole magnets at a distance of 1m to the interaction region are also shown. The detailed design is under preparation.

The stringent requirements on the high-rate capability of the tracking system make a silicon-type detector for the inner tracking system (forward and rear silicon disks together with several silicon barrel layers) together with a GEM-type detector for the outer tracking system (forward and rear GEM-type tracking disks with several barrel GEM-type tracking layers) a natural choice.

The forward and rear detector systems have not been considered so far. The design and location of those detector systems has to be worked out in close collaboration to accelerator physicists since machine magnets will be employed as spectrometer magnets and thus determine the actual detector acceptance and ultimately the final location. It is understood that demands on optimizing the rear/forward detector acceptance might have consequences on the machine layout and is therefore an iterative process.

2.4.6.3 Requirements on the eRHIC tracking detector design, R&D and construction facility

A hermetic inner and outer tracking system will be a crucial component of the central part of a future eRHIC detector. As pointed out in the previous section, the choice of an inner silicon and outer GEM-type tracking detector would be a natural choice considering the requirement for a high-rate tracking device.

It is foreseen to strongly engage in the design and construction of the eRHIC tracking system. This would therefore make use of the existing (LNS silicon laboratory) and proposed (Micro-pattern detector facility) detector facilities at MIT as pointed out in the beginning.

The following provides an outline of the usage of the MIT-BATES infra-structure and personnel for the period of FY06-FY08 and beyond:

- Conceptual design of the eRHIC tracking system together with 2 MIT-BATES staff physicists
- Mechanical design of the inner and outer tracking system (A similar effort is already foreseen for the STAR tracking system and would thus provide a continuation in using MIT-BATES infra-structure and personnel having worked on similar tracking systems)
- Silicon sensor testing and characterization, module assembly and bonding could be carried out by the existing LNS silicon laboratory
- GEM-foil testing, inspection and final GEM tracker module assembly could be carried out in the proposed MIT-BATES micro-pattern facility
- Final integration and test in a larger clean construction area of at least 1000sq. feet in size

The following requirements on personnel and infra-structure are foreseen with the beginning of the actual eRHIC tracker construction:

- Micro-pattern facility including staff
- LNS silicon facility including staff
- 1+1 staff physicists to coordinate local design and construction efforts (mechanical integration and DAQ)
- 1 mechanical engineer for mechanical design including support by

- technicians (4) for detector assembly (2) and final integration (2) and availability of mechanical and electronics workshops
- Clean workspace with crane support (no clean room requirement) for final integration and testing

It is expected to present a conceptual design report on the eRHIC detector design towards the end of the current decade. It will be crucial starting in FY06 that one staff physicist is engaged in the tracker design work. An increase in staff as outlined above is necessary once the eRHIC detector has been approved.
This detector design and construction effort for a future eRHIC tracking detector will provide an ideal learning environment for undergraduate and graduate students and a stimulating research facility for future research associates. This future effort will allow MIT to be at the fore-front of fundamental QCD physics at a future eRHIC facility at Brookhaven National Laboratory.

2.5 Other Research Opportunities

2.5.1 Development of a Polarized ^{3}He Ion Source for RHIC

M. Farkhondeh, W. Franklin, R. Milner, E. Tsentalovich

2.5.1.1 Introduction

Study of the spin structure of the nucleon is a fundamental problem of major current interest. Experiments at SLAC, CERN and DESY over the last two decades have determined that the contribution of the quarks to the nucleon's spin is only about 25%. Major experimental efforts are in progress at CERN and at RHIC to directly determine the contribution of the gluons to the nucleon's spin. A substantial group at LNS under the leadership of Prof. Bernd Surrow is collaborating in the STAR experiment at RHIC-spin.

In all experimental investigations of nucleon spin to date, it has been essential to carry out measurements on both isospin configurations of the nucleon, namely both the neutron and proton. The neutron contains different combinations of quark flavors and provides a second nucleon system, different to the proton, with (presumably identical) gluon distribution. In the RHIC-spin program, a polarized neutron beam would allow an independent determination of nucleon spin structure which at a minimum would provide important verification of the proton measurements. In the event of surprising results on the proton, the neutron beam would become absolutely essential. Further, with the eventual realization of eRHIC, the ability to have both polarized proton and polarized neutron beams in RHIC is essential for a test of the fundamental Bjorken Sum Rule.

Nature does not provide us with readily available intense beams of free polarized neutrons. Thus, either polarized deuterium or polarized ^{3}He has been used as an effective polarized neutron target in deep-inelastic scattering measurements to probe the nucleon spin structure. In the case of RHIC, manipulation of the spin of the polarized deuteron is technically formidable because of the small magnitude of the deuteron's magnetic moment. ^{3}He, on the other hand, posseses a magnetic moment close to that of the free neutron and thus in RHIC a polarized ^{3}He beam can be manipulated (up to a sign) similarly to the polarized proton. Thus, to realize a polarized neutron beam in RHIC requires injection of an intense beam of highly polarized ^{3}He ions. It is the goal of this collaborative effort to develop such a source over the next five years.

2.5.1.2 Polarized ion source

It is planned to develop in collaboration with Prof. E. Hughes's group at Caltech and Dr. J. Alessi's group at Brookhaven National Laboratory an intense source (~ 500 particle μA, i.e. 3 X 10^{15}/sec) of highly polarized (~ 70%) ^{3}He ions which will be injected into RHIC. Polarized ^{3}He ions sources have been successfully realized using a number of techniques. A Lamb shift polarized ^{3}He ion source was developed at the University of Birmingham, United Kingdom [2.5.1] and delivered 50 particle nA of 65% polarized ^{3}He. A metastability exchange optically pumped source was developed by a Rice University-Texas A&M collaboration [2.5.2] and delivered 8 particle μA of 11% polarized ^{3}He. A source based on the Stern Gerlach method was developed at Laval University, Canada [2.5.3] and delivered 100 particle nA with high polarization up to 95%. Spin transfer collisions can also be used for polarized $^3He^{++}$ production. This scheme is under development at RCNP (Osaka, Japan) [2.5.4].

We propose to develop a source of polarized ^{3}He atoms based on the technique of metastability exchange optical pumping [2.5.5]. In this method, ^{3}He gas at typically 1 torr is contained in a glass bulb and a weak RF discharge is maintained in the gas. Metastable atoms in the 2 $^3S_1$ state are produced in the discharge and may be polarized by means of optical pumping with circularly polarized (2 ^{3}P – 2 ^{3}S) 1.083 μm light. This polarization is subsequently transferred to the much more numerous 1 $^1S_0$ ground-state atoms via spin-exchange collisions. Typically, a laser system tuned to the resonance 1.083 μm line is used for the optical pumping. The polarization in the glass cell can be determined using a measurement of the circular polarization of the 667 nm line in the discharge. Modern lasers will allow much higher polarized source figure-of-merit compared to the pioneering efforts described previously.

An internal target based on this principle was developed at MIT-Bates [2.5.6] and has been successfully used at IUCF [2.5.7], DESY/HERMES [2.5.8] and at NIKHEF. The laser used was a modified Nd:YAG system using a flashlamp pumped Nd:LMA . Typical output powers were 2 W at 1.083 μm yielding target polarizations of 50% at flow rates of 2 x 10^{17} ^{3}He atoms/sec. Recently, ytterbium fiber lasers have produced 20-40 W of 1.083 μm radiation for metastability exchange optical pumping [2.5.9]. Large volume systems at the University of Mainz [2.5.10] have delivered polarizations of over 70% at a polarization rate of 8 x 10^{18} atoms/s as shown in figure 2.5.1.

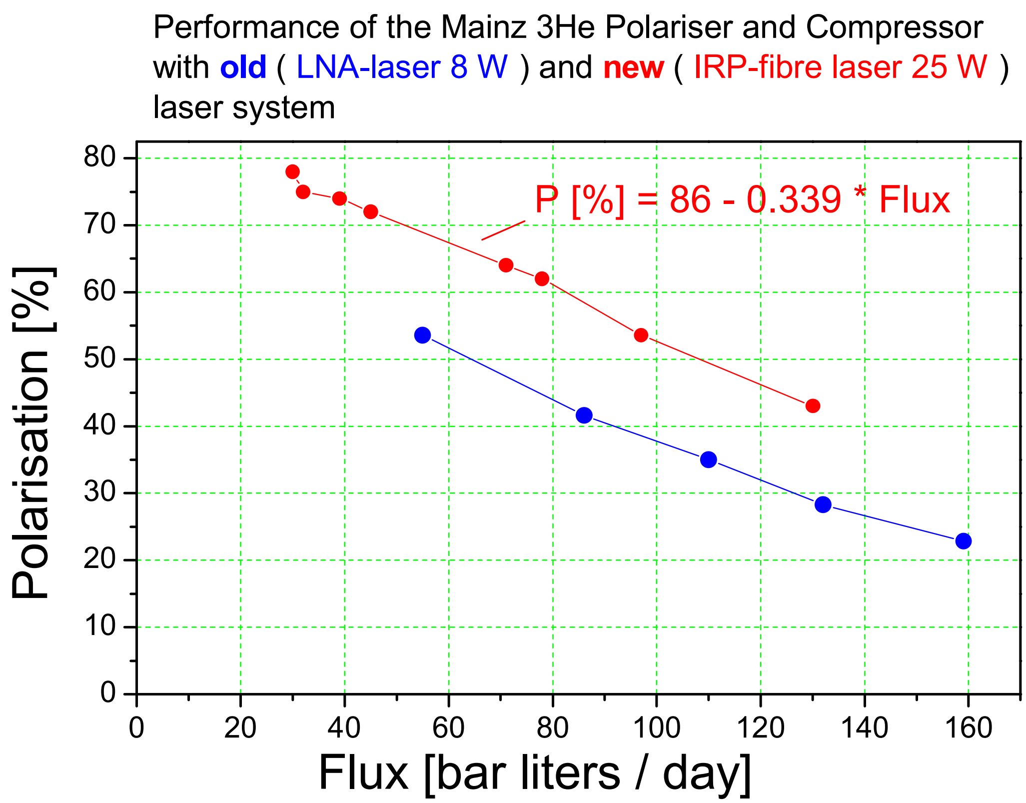


Figure 2.5.1 *The polarization of the 3He gas as a function of the polarization rate using a 25 W fiber laser system [2.5.10].*

2.5.1.3 EBIS source at RHIC

An Electron-Beam Ion Source (EBIS) is under development at BNL as an alternative to the Tandem heavy ion injector for RHIC [2.5.11]. It is proposed to use the EBIS to produce $^3He^{++}$ by ionization of the polarized ^{3}He gas which is fed from the glass pumping cell. The ionization in the EBIS is produced in a 50 kG magnetic field, which preserves the nuclear ^{3}He polarization while in the intermediate single-charged $^3He^+$ state. The ionization efficiency to the double-charged $^3He^{++}$ will be close to 100% and the number of ions is limited to maximum charge which can be confined in the EBIS. From experiments with Au^{32+} ion production, one expects about 2.5 x 10^{11} ions to be produced and extracted for subsequent acceleration and injection to RHIC. Figure 2.5.2 shows a schematic layout of the polarized ^{3}He ion source.

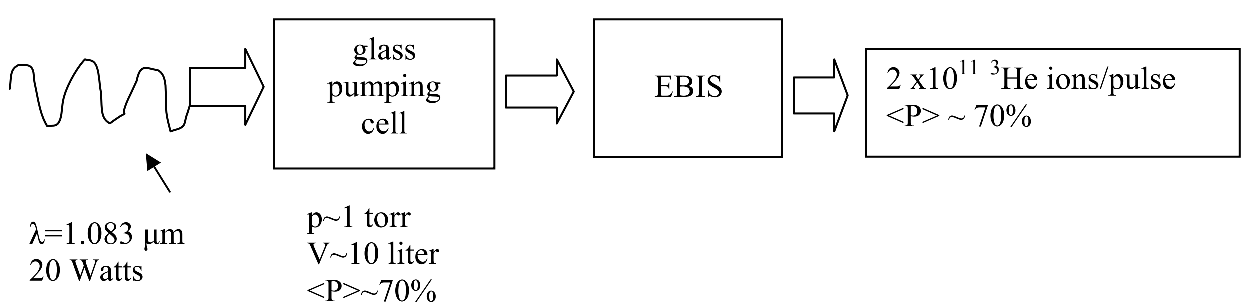


Figure 2.5.2. *Schematic layout of proposed polarized ^{3}He ion source for RHIC.*

2.5.1.4 Polarimetry

Once the polarized ^{3}He ions are extracted from the source they will be accelerated using an RFQ to an energy of 300 keV/amu, i.e. 900 keV $^3He^{++}$. The polarization of the ions will be measured using a fewbody nuclear reaction. One attractive polarimeter scheme would be to use the reaction $^3He + ^2H \rightarrow p + ^4He + 18.35$ MeV. Such a technique has been successfully used [2.5.11] to measure the polarization of a 5% polarized He ion beam of intensity 4 μA . In this experiment the polarized ^{3}He ion beam was stopped in a frozen D_2O target and the polarization of the 15 MeV protons measured in a second scattering on ^{4}He.

2.5.1.5 Plan

In the years FY04 and FY05 metastability exchange optical pumping using the new generation of fiber lasers will be developed at both Caltech and MIT-Bates. At Bates a test stand is active in the development of a polarized He target for the Bates Large Acceptance Spectrometer Toroid (BLAST). In addition, the polarimeter technique for measurement of the $^3He^{++}$ polarization from the EBIS source will be developed.

In FY06-07 it is planned to mount an experiment in which polarized ^{3}He atoms will be fed into the EBIS prototype source, will be extracted as ions, accelerated and their polarization measured using a polarimeter. The parameters for optimal polarized ^{3}He ion source delivery to RHIC will be established.

Based on the results of this test experiment, in FY08 design of an optimized polarized ^{3}He source for operation in conjunction with the full scale EBIS will be carried out.

A major focus of the ion source development will be to attract students at both Caltech and MIT. Past experience has shown that this type of table-top development is a strong attractor for students and particularly suitable for undergraduate research projects. It is envisaged that students will play a major role in the eventual commissioning of the source at BNL.

2.5.2 Proposal for a Low Background Laboratory at the Bates Site

P. Fisher

A large class of experiments has grown over the past fifteen years, which seek to detect very rare decays in low background environments. This interest grows from recent experimental results, which show neutrinos are massive and oscillate, and that 93% of the matter in the universe is of an unknown nature. The Physics Department and Laboratory for Nuclear Science have always had a strong interest in these areas (axion experiment and AMS) and interest is growing (Max Tegmark and Kavli Proposal). Experiments include neutrinoless double beta decay, dark matter searches and low energy neutrino detection.

Such experiments are carried out in sites deep underground in order to reduce backgrounds from cosmic rays, particularly muons and neutrons created by interactions between muons and matter surrounding the experiment. The measure of depth is 1 meter water equivalent (MWE) which corresponds to about 30 cm of rock. Deep sites include Soudan (MINOS and CDMS), SuperKamiokande and Gran Sasso, all of which have depths of order 1000 MWE. For the purposes of detector development and early background assessments, a much shallower site, located close to significant infrastructure, is an invaluable resource. For example, all the Cryogenic Dark Matter Search (CDMS) experimental results so far come from a 30 MWE site at Stanford University. A site close to the detector fabrication facilities and workshops at Berkeley and Stanford proved invaluable for the development of the sensors used in the experiment.

The Bates site provides a natural setting for such a facility for MIT and other Boston area universities. Located thirty minutes from MIT, an underground lab at Bates would allow rapid development of new detectors at MIT's Microtechnology Laboratory (MTL) and Lincoln labs. Once debugged, these detectors would then be deployed at deeper sites. General requirements for a developmental underground lab are

- At least 10 MWE overburden in all directions from lab area. This reduces the cosmic ray background by a factor of five, making efficient active vetoing possible.
- A hermetic active veto system. Historically, scintillator with phototubes has been used, but a gas detector may be possible.
- At least 500 sq. ft. usable area with overhead crane for moving shielding.
- A drop pit six feet deep and two feet square for lowering the outer cryostat on a helium dilution refrigerator.
- Cabling to low noise electronics and counting room.
- Clean room area.
- Good access to liquid helium and nitrogen.
- Nearby machine and electronic shops

A schematic layout is shown in Figure 2.5.3.

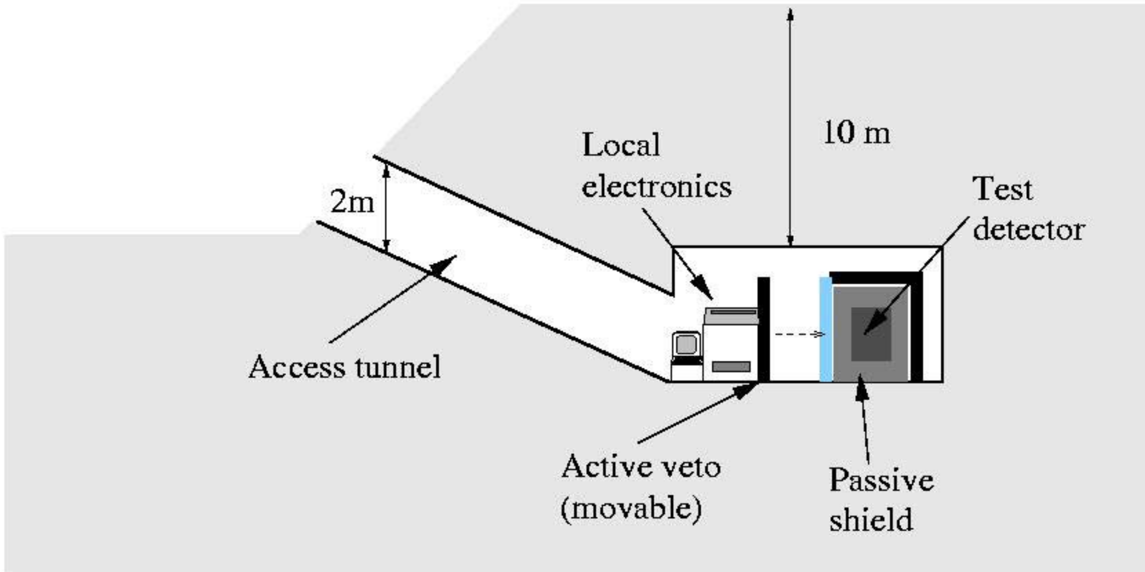


Figure 2.5.3. *Schematic layout for underground laboratory.*

The laboratory could be located off of a subbasement or a specially dug shaft. It should be possible to run all services (electrical, electronic, ventilation and water) along the access tunnel.

2.5.3 Data Acquisition Capability

B. Knuteson

The MIT CDF group has been responsible for the design and successful operation of the Event Builder at CDF for the past ten years, in both Fermilab Tevatron Runs I and II. The Event Builder combines event fragments from different subdetectors read out of Level 2 of the CDF trigger into a single processor at Level 3 in which a global event decision can be made. The Event Builder thus takes the form of a networking switch, and controlling software to manage traffic flow.

The increased luminosity expected over the next five years of Tevatron running will result in an event rate that exceeds the capability of the current Event Builder. The MIT CDF group is responsible for upgrading the Event Builder in Tevatron Run IIb to handle the expected 1 kHz event rate at 500 kB per event, for a total throughput of 500 MB per second.

The current Event Builder is implemented using hardware based on a proprietary telecommunications technology. The impressive technical gains in commercial networking technologies over the past few years makes gigabit Ethernet the logical choice for the Run IIb Event Builder. The gigabit Ethernet switch for the final system will arrive at Fermilab in the next two weeks. Commercial boards have been ordered for reading the data from VME crates out of Level 2 into the switch. The primary task remaining is the writing of software that will enable these pieces to work together for robust data taking at CDF.

A full time programmer familiar with networking and based at MIT will play an extremely important role this project. Part time expertise has been pulled in from both CDF and D0, and it will be absolutely crucial to have a full time developer for this project over the next two years. A full time person located at MIT will enable us to make excellent use of undergraduate and beginning graduate students located on campus; without this local full time support, effective student involvement in this project will be difficult.

The Run IIb Event Builder upgrade is due, fully commissioned, for installation during the summer shutdown in June 2005. The support of Bates in this effort, in the form of one full time programmer with networking expertise, will be invaluable. This person will allow us to fully leverage existing expertise at Fermilab, and student horsepower based at MIT. A software engineer with networking expertise will be a future resource for Bates, looking ahead toward MIT's data acquisition responsibilities at CMS, and future computing projects at the LHC.

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Section 3.0 ORGANIZATION

The structure of the proposed research laboratory is a match of the areas of expertise and skill of current Bates personnel with the requirements of the proposed research and development projects as well as plausible future needs of the MIT-LNS research groups. The resulting professional fields of competence of a Bates research laboratory have been identified as:

- Accelerator physics, particularly electron storage rings
- RF technology
- Polarized particle injectors
- Polarized and cryogenic targets
- Detector development, design and construction
- Magnet and power supply technology
- Vacuum, particularly UHV technology
- Data acquisition and control

While these fields of expertise are required for the currently proposed R&D projects, their strength will need to vary in time to match the varying requirements.

To maintain effectiveness in the above areas of expertise a staff of 35 FTE is required. Of these 35 FTEs three would be newly hired staff physicists: two in the area of accelerator physics to work on eRHIC design and one in the area of micro-pattern detector development. It is proposed to structure this staff as follows:

Research physicists	6 FTE
Accelerator physicists	6
Mechanical Engineering	10
Electrical Engineering	10
Administration	2
Computing support	1
Total	35 FTE

The scientists and engineers will be organized into Divisions as indicated schematically below. The Physics Division will have four principal activities: Accelerator physics, Detector development, Data acquisition and Polarized beams and targets.

The Laboratory will be led by a Manager, who will be a senior staff physicist. The priorities of the Laboratory will be determined by a standing LNS committee.

Physics Division

- Accelerator physics (6)
- Detector development (3)
- Data acquisition (2)
- Polarized beams and targets (1)

Engineering Division

- Mechanical (10)
- Electrical (10)

Table 3.1. *Summary table for manpower required for the proposed research program at Bates for FY06-08.*

Research Project		Total FTE		
		FY06	FY07	FY08
Q_{weak}				
QTOR (toroidal magnet)	Mech. Engineer	1	0.5	
	Elec. Engineer	0.5	0.5	0
	Designer	1.5	0.5	0
	Technician	6	2	0
Target design	Physicist	0.25		
	Mech. Engineer	0.5	0.25	
	Elec. Engineer	0.25	0.25	
	Designer	0.5	0.25	
	Technician	0.5	0.25	
Mini-torus	Physicist	0.25		
	Mech. Engineer	0.25	0	
	Elect. Engineer	0.25		
	Designer	0.5		
	Technician	0.5	0	
Beam line hardware	Physicist	0.5		
	Mech. Engineer	0.5	0.25	
	Elec. Engineer	0.25		
	Designer	0.5	0.5	
	Technician	0.75	0.5	
DAQ/Software	Physicist	1.0	1.0	
	Computer prog.	2.0	1.0	
STAR				
Forward hadron calorimeter	Physicist	1	1	1
	Engineer	1.5	1.5	1.5
	Technician	3	3	3
DAQ1000	Engineer	0.5	0.5	0.5
	Programmer	0.5	0.5	0.5
	Technician	1	1	1
Micro-pattern detector facility	Physicist	1.5	1.5	1.5

eRHIC				
Machine design	Photoinjector physicist	0.5	1.5	1.5
	Accelerator physicist	6.0	6.0	5.5
	Polarimeter physicist	0.5	1.0	1.0
	RF engineer	2.0	3.0	3.0
	Mech. Engineer	1.0	1.5	1.0
	Elec. Engineer	0.25	0.25	0.25
	Photoinjector Technician	1.0	1.0	1.0
Detector design	Physicist			1.0
	Engineer		0.5	1.0
	Technician		0.5	2.0
DAQ development				
	Software Engineer	0.5	0.5	0.5
Polarized He-3 Source Development				
	Physicist	0.5	0.5	0.5
	Engineer	0.5	0.5	0.5
	Technician	0.5	0.5	0.5
Low Background Laboratory				
	Physicist	0.5	0.5	0.5
	Engineer	0.5	0.5	0.5
	Grand Total	**42.50**	**35.00**	**29.25**

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